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Neuromorphic Photonics

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Abstract

Neuromorphic photonic applies concepts extracted from neuroscience to develop photonic devices behaving like neural systems and achieve brain-like information processing capacity and efficiency. This new field combines the advantages of photonics and neuromorphic architectures to build systems with high efficiency, high interconnectivity and paves the way to ultrafast, power efficient and low cost and complex signal processing. We explore the use of semiconductor lasers with optoelectronic feedback operating in self-pulsating mode as photonic neuron that can deliver flexible control schemes with narrow optical pulses of less than 30 ps pulse width, with adjustable pulse intervals of -2 ps/mA to accommodate specific Pulse Position Modulation (PPM) coding of events to trigger photonic neuron firing as required. The analyses cover in addition to self-pulsation performance and controls, the phase noise and jitter characteristics of such solution.

Keywords: neuromorphic, neuron, optoelectronic feedback, photonic integration, self-pulsation, control theory, semiconductor laser, photonic tensor core

1. Introduction

Von Neumann digital computer architecture [1] that existed since the 1940s and still being the only viable architecture for computers cannot keep up with the exponential speed needed, to process data for machine learning and artificial intelligence applications as we move into a internet of things (IoT) dominated world. This architecture cannot keep up with Moore's law that predicted the count of transistors in a CPU to double every 2 years, while at the same time, the CPU clock rate reached a ceiling at 4 GHz due to prevalence of current leakage in nanometric nodes. Hence, the move to multicore architecture is running against the power requirements for simultaneously powering these cores. All this can be traced to the excess amount of energy consumption of digital switching and the bandwidth limitation of the metal interconnects. These listed bottlenecks are driving the efforts for a new computing architecture towards the use of neuromorphic photonics, especially with the fast track to maturity that photonic integration has taken with III-V material processing and recently with Silicon photonics. Photonic integration offers a rich library of various components with reduced latency, higher bandwidth, and energy efficiency. It also facilitates nonlinear optoelectronic devices along with photonic/electronic integration and compact packaging.

The chapter is organized as follows: Section 2 covers background information on Neurons, and the efficiency of information processing in the human brain compared with other available technologies, it also covers addresses photonic tensor cores, the basic architecture of photonic neuron, and how the information is coded. Section 3 introduces photonic neuron based semiconductor lasers with

optoelectronic feedback, along with feedback control theory, and the equations covering self-pulsating mode of laser neuron system. Section 4, presents simulation results and noise analysis of the photonic neuron system, while Section 5, provides the concluding remarks of this work.

2. Technology survey

In this section, we survey competing technologies and their architectures while comparing them to the ultimate information processor in the human brain.

2.1 Neurons

The human brain contains around 100 billion neurons. It is the most complex system for information processing in existence, with an execution power of 10^{18} (multiply-accumulate matrix) MAC/s with only 20 Watts power needed [2, 3]. Each of those neurons has an average of 10^4 inputs of tiny neurotransmitter junctions known as synapse. This translates into 10^{15} of synapses connections, while the bandwidth of the signal processed in the brain is 1 KHz max. The computational efficiency of the brain is less than 1 AttoJoules/MAC while supercomputers today have an efficiency of 100 picoJoules/MAC, in other word, the magnitude of the brain efficiency is 8 orders better than supercomputers as can be seen in **Figure 1**. The neuron by definition is a single brain cell. It communicates with other neurons with electrical impulses via thousands of synapses. The neurotransmitters (chemical secretions) electrical input to the neuron comes from other neurons with different weights. The signal level needs to exceed a certain threshold value to cause the neuron to fire, sending a series of electrical spikes to other neurons. Below threshold input, the neuron output is very small and linear, while above threshold, the neuron output is large and nonlinear. This behavior is similar to how lasers operate; below threshold, the optical output is made of spontaneous emission, low output incoherent optical power, while above threshold, stimulated emission dominates and produce large coherent optical light output. A key requirement to have the laser behave as a neuron is to include an absorber section to limit the spontaneous emission output below threshold levels. These electrical activities in the brain can be monitored using ElectroEncephaloGraph (EEG), these signals can be

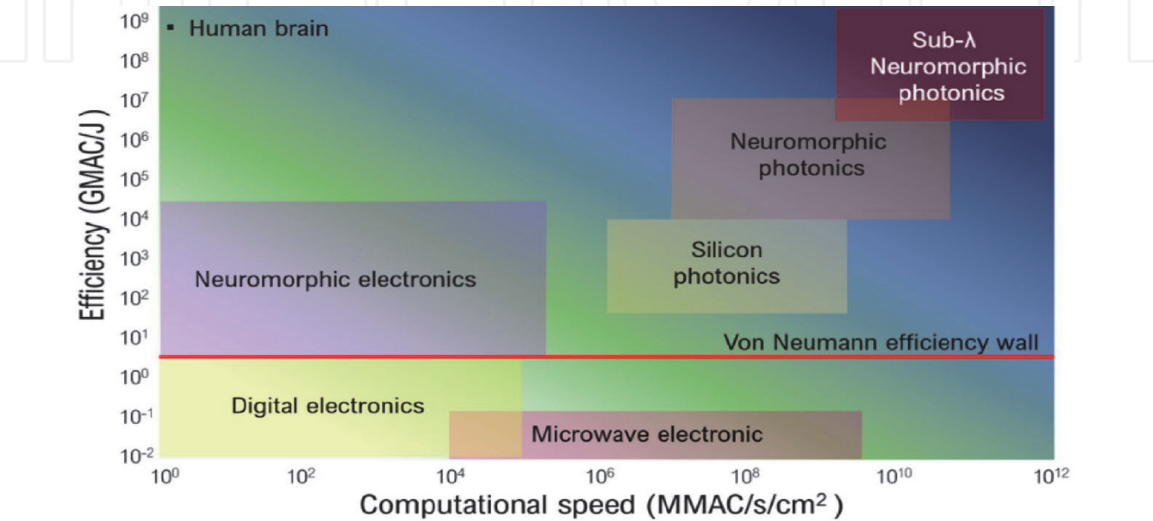


Figure 1. Comparing computational speed with efficiency for various elements of available technologies [4].

strongly correlated with different cognitive tasks, but they appear as a chaotic signal plot when plotted against time from physics and mathematics perspectives.

2.2 Photonic tensor core

The key driver for neuromorphic photonic approach especially in Machine-Learning, is the move from electronic processing approach in hardware systems such as Google’s Tensor Processing Unit (TPU) which relies on grinding through stacks of repeated matrix multiplications that require immense amount of power. Neuromorphic photonic approach facilitates a photonic solution that is a modular photonic tensor core (PTC) where all matrix calculations get processed in the optical domain. This PTC process provides three orders of magnitude more computing power than TPU with processing of the multiply-accumulate matrix (MAC) operations. TPU data also exhibit long run times especially when performing image processing. While PTC can use the wave nature of light to, directly perform summation using coherent addition of wave amplitudes, and multiplications can result from the interaction of optical waves with matter. At the same time, and similar to the behavior of biological neurons, where each neuron can both process and store data, PTC replicates these functions, which dramatically reduces latency [5].

2.3 Photonic neuron

The neuron consists of an input stage that is a linear combination (weighted addition) of the outputs of the neurons feeding it. The combined signals from the input stage are integrated to produce a nonlinear response as dictated by the activation function see **Figure 2**.

This neuron must perform three mathematical operations:

- 1. Vector (weighting) multiplication
- 2. Spatial summation
- 3. Nonlinear transformation

All inputs must be of the same nature as outputs.

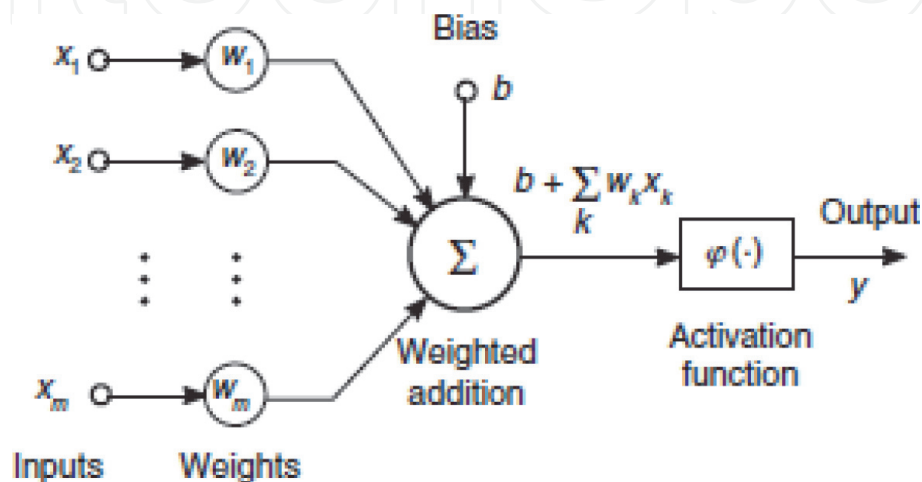


Figure 2.
Neuron signal flow model [6].

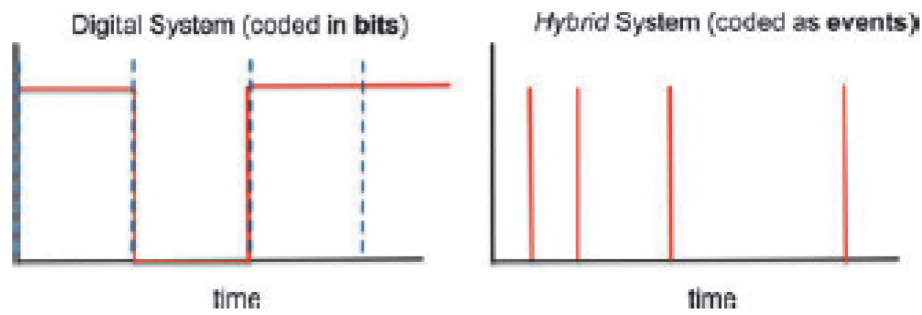


Figure 3. Spiking neuron information encoding scheme of events rather than bits [6].

2.4 Information coding

In order to have an efficient signal modulation scheme, a hybrid combination of analog and digital signal representation need to be implemented that mimics the way the brain encodes information as events in time. The type of a well-known modulation scheme used in optical communication systems called Pulse Position Modulation (PPM) [6, 7].

This modulation format exploits the efficiency of analog signals and at the same time reduces the noise accumulation that distorts analog signals (see **Figure 3**).

3. Semiconductor lasers with optoelectronic feedback as photonic neuron

Semiconductor lasers are widely used in many applications for both digital and analog signal processing. For the past two decades, specifications of these lasers have addressed many specific applications by tailoring the laser design parameters to meet specific performance target. While the aim of this work is to use low cost lasers with generic specifications, modify and enhance their essential performance parameters to behave as a photonic neuron in addition to the applications addressed in [8] by using electronic feedback for triggering self-pulsating behavior necessary for spiking neuron model. The main driver behind this work is to facilitate photonic integration, improving laser modulation bandwidth and increasing laser relaxation oscillation frequency. The performance for all these applications is analyzed in both time and frequency domains. Mainly, by adjusting the feedback loop settings so it can operate outside its stable regime but just ahead of the chaos mode, so the laser can run in self-pulsation mode. This provides the use of the laser drive current as a single point of control for the pulsation rep-rate and.

3.1 Basic control theory

The theory behind this work is based on the classical control theory of negative feedback. Recent work by [9], has presented a rigorous, yet simple and intuitive, non-linear analysis method for predicting injection locking in LC oscillators.

A system with a negative feedback control loop is shown in **Figure 4**.

It consists of a forward-gain element with transfer function $A(s)$, with s is the Laplace operator and can be replaced by $(j\omega)$ feedback element with transfer function $B(s)$.

Where $A(s)$ represents laser transfer function, $B(s)$ represents the feedback loop transfer function, x is the injection Current and y is the Optical output power.

The closed loop transfer function of such system is:

$$T(s) = \frac{y}{x} = \frac{A(s)}{1 + A(s) * B(s)} \tag{1}$$

This system can be linearized by making the gain product $A(s) * B(s) \gg 1$.
With this condition, the transfer function becomes dependent solely on the feedback gain coefficient and response of the feedback loop, which becomes linear:

$$T(s) = \frac{1}{B(s)} \tag{2}$$

A feedback loop can oscillate if its open-loop gain exceeds unity and simultaneously its open-loop phase shift exceeds π . There are poles that are present in the closed loop configuration with at least one pole of an unstable loop lies in the right half of the s-plane in **Figure 5**.

Analysis of stability of this system can be done according to the Nyquist Criterion [10] by investigating pole location.

It is based on Nyquist plot where the open-loop transfer function is analyzed with a plot of real and imaginary parts. Where stability of the closed-loop system is determined If poles are present in the Left Half (LHP) of the s-Plane.

If poles are present in the Right Hand Plane (RHP), the closed-loop system becomes unstable. In brief, the Nyquist criterion is a method for the determination of the stability of feedback loop systems as a function of an adjustable gain and delay parameters in the feedback section. It simply determines if the system is stable for any specified value of the feedback transfer function $B(s)$.

For the self-pulsation mode, it is well known that an active circuit with feedback can produce self-sustained oscillations only if the criterion formulated by Barkhausen [10] is fulfilled. This criterion is defined as when the denominator of

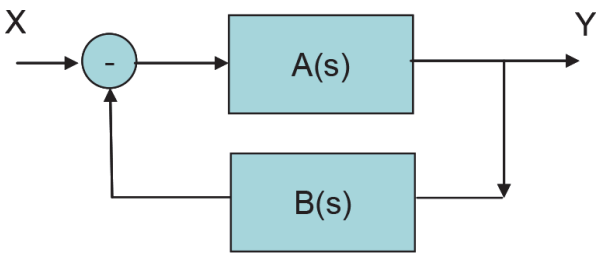


Figure 4.
Negative feedback loop system [8].

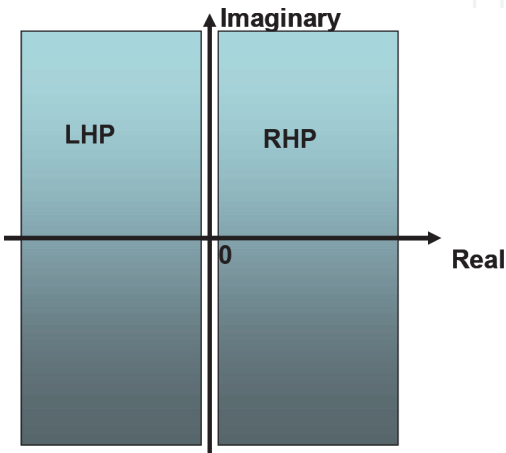


Figure 5.
S-plane plot.

the closed loop transfer function is zero. The poles in this self-pulsation mode need to be located outside RHP (Chaos mode) and LHP (Stable mode), only present up and down on the imaginary axis of the s-plane plot with a zero value on the real axis and where the phase of this transfer function:

$$\Delta T(j\omega) = 0 \Rightarrow \omega = \omega_0 \tag{3}$$

$$|T(j\omega_0)| = 1 \tag{4}$$

Eqs. (3) and (4) are the phase and gain conditions, respectively. Based on Barkhausen criterion, the oscillation frequency is determined by the phase condition (3).

3.2 Self-pulsating system

There have been numerous publications on the effects of lasers with electronic feedback [11–13], covering mainly the various states from operating this system. The in this work is on increasing the feedback loop delay to achieve self-pulsation and chaos modes.

Starting with the DFB laser characteristics that are modeled using the well-known rate equations [8, 14] that have been modified to include the electronic feedback parameters.

$$\frac{dN(t)}{dt} = \frac{I(t)}{q * V_a} - g_0 \frac{[N(t) - N_0] * S(t)}{1 + \epsilon * S(t)} - \frac{N(t)}{\tau_n} + \left[\frac{\omega_n}{2\pi} * (\rho * S[t - \tau]) \right] \tag{5}$$

$$\frac{dS(t)}{dt} = \Gamma * g_0 \frac{[N(t) - N_0] * S(t)}{1 + \epsilon * S(t)} - \frac{S(t)}{\tau_p} + \frac{\Gamma * \beta}{\tau_n} * N(t) \tag{6}$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2} \alpha \left[\Gamma * g_0 [N(t) - N_0] - \frac{1}{\tau_p} \right] \tag{7}$$

Where Eq. (5), represents the carrier density equation with the feedback terms, ρ represents the feedback loop gain, τ represents the feedback loop propagation delay and ω_n represents the 3 dB bandwidth of the amplifier circuit. Eq. (6), represents the photon density, and Eq. (7) the optical phase.

The laser parameters included in these equations are listed in **Table 1**.

Symbol	Value	Dimension	Description
I(t)	—	A	Laser current
S(t)	—	m ⁻³	Photon density
Γ	0.44	—	Optical confinement factor
g ₀	3x10 ⁻⁶	cm ⁻³ /s	Gain slope
N(t)	—	m ⁻³	Carrier density
N ₀	1.2x10 ¹⁸	cm ⁻³	Carrier density at transparency
ε	3.4x10 ⁻¹⁷	cm ³	Gain saturation parameter
τ _p	1.0x10 ⁻¹²	s	Photon lifetime
β	4.0x10 ⁻⁴	—	Spontaneous emission factor
τ _n	3.0x10 ⁻⁹	s	Carrier lifetime
V _a	9.0x10 ⁻¹¹	cm ³	Volume of the active region
φ	—	—	Phase of the electric field from the laser

Symbol	Value	Dimension	Description
α	3.1	—	Line-width enhancement factor
$P(t)$	—	W	Optical power from laser
Q	1.602×10^{-19}	C	Electronic charge
η	0.1	—	Total quantum efficiency
h	6.624×10^{-34}	J.s	Plank's constant
ω_n	75.4×10^9	Rad/s	3 dB Bandwidth of amplifier Circuit
σ_g	2×10^{-20}	m^2	Gain cross section

Table 1.
Paramters used in this work [14].

The optical output power from the laser is represented in Eq. (8)

$$P(t) = \frac{S(t) * V_a * \eta_0 * h * \nu}{2 * \Gamma * \tau_p} \tag{8}$$

The system being analyzed which includes the laser and the feedback loop is shown in **Figure 6**.

This system consists of a wideband monitor diode located at the back facet of the laser cavity and electrical amplifier. This implementation using the wideband back-facet monitor [15], provides the means to control and manage the short propagation delay in the feedback loop, this is necessary layout in order to achieve the desired performance characteristics. It also provides a mechanically stable system. The key parameters calculated from the model equations are the relaxation oscillation frequency (ROF), and the damping factor. The system is configured to account for the delay, gain and bandwidth of the feedback loop and are expressed in the following forms:

$$f_r = \frac{1}{2\pi} \sqrt{K - \frac{1}{2}(\gamma_d)^2} \tag{9}$$

The laser transfer function H is of the form:

$$H(j\omega) = \frac{K}{[(j\omega) * (j\omega + \gamma_d)] + K} \tag{10}$$

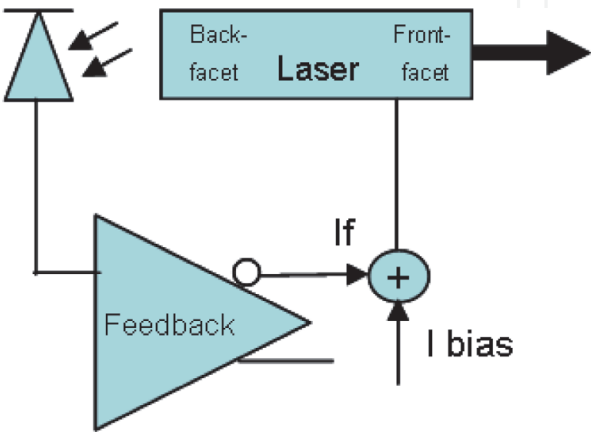


Figure 6.
Laser system with feedback.

Where K is:

$$K = \left[\frac{\Gamma * g_0}{q * V_a} (I_{Bias} - I_{th}) \right] \left[1 - \frac{\Gamma}{q * V_a} * \epsilon * \tau_p (I_{Bias} - I_{th}) \right] \quad (11)$$

and γ_d , the damping factor, is of the form:

$$\gamma_d = \frac{1}{\tau_n} + \left[\frac{\Gamma * g_0}{q * V_a} \left(\tau_p + \frac{\epsilon}{g_0} \right) ((I_{Bias} - I_{th})) \right] \left[1 - \frac{\Gamma}{q * V_a} * \epsilon * \tau_p (I_{Bias} - I_{th}) \right] \quad (12)$$

In the feedback loop, the amplifier transfer function A is of the form

$$A = \frac{-\rho}{1 + \left(\frac{j\omega}{\omega_n} \right)} \quad (13)$$

Where ρ is the feedback gain, and ω_n is the 3 dB bandwidth of the amplifier circuit.

For the delay transfer function B is of the form

$$B = e^{-j\omega\tau} \quad (14)$$

Where τ is the propagation time delay of the feedback loop system.

Based on the well-known control theory of systems with negative feedback [16], the complete transfer function on this complete laser system Y is of the form

$$Y(j\omega) = \frac{H}{1 + (H * A * B)} \quad (15)$$

Using the parameters listed in **Table 1**, the calculated laser threshold current is 9.4 mA. The slope efficiency is calculated at 0.04 mW/mA.

4. Simulation results and discussion

Setting up the system to operate in self-pulsating state with fixed FB loop gain of -0.05 and loop delay of 50 ps, the physical phenomenon of self-pulsation process is described as the sharpening and extraction of the first spike of the relaxation oscillation frequency (ROF) of the laser cavity. The feedback sharpens the falling edge of the first spike and suppresses the subsequent spikes.

Hence, lasers with stronger ROF generate shorter pulses. We show the system transfer function ($Y(j\omega)$) magnitude and phase plots in **Figure 7**. What we see is in the case where the feedback loop is applied an enhanced second peak in the magnitude transfer function plot of **Figure 7** which indicates the generation of sharp pulsation. The inverse of the frequency peak corresponds to the pulse interval in the time domain.

A capture of the time-domain picture of the self-pulsation mode, is shown in **Figure 8** where the set points are at 50 mA bias current with feedback delay of 50 ps and feedback gain of -0.05 . This plot shows the output power of the system where the pulse interval is 147 ps and the pulse width is 50 ps.

Figure 9 shows the change of the pulse interval (Free Spectral Range) as a function of the bias current. The pulse interval can be fine-tuned over a range > 50 ps. The shortest pulse interval was achieved for these particular laser parameters from **Table 1**. When setting the delay at 30 ps and the gain at -0.05

with 50 mA bias current was 80 ps with pulse width of 30 ps. These limitations on the pulse width are governed mainly by the laser carrier lifetime in the laser structure. This is a crucial feature for photonic neurons, as the pulse interval can be adjusted by modulating the laser current, where asymmetric spacing is needed based on specific events that lead to neuron firing.

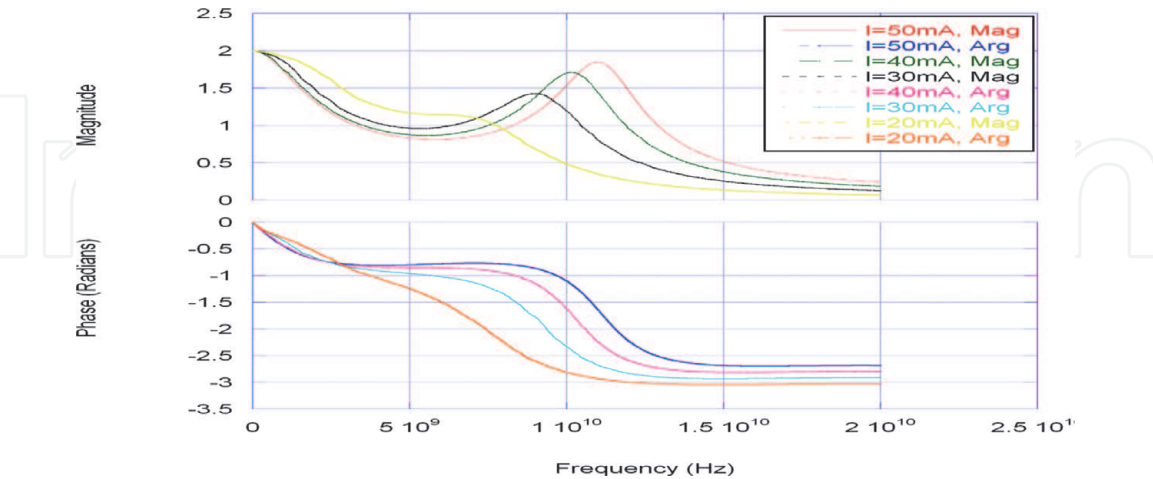


Figure 7. Magnitude and phase plots of the laser transfer function with feedback loop in self-pulsation regime for various current values (FB loop gain = -0.05 , FB loop delay = 50 ps).

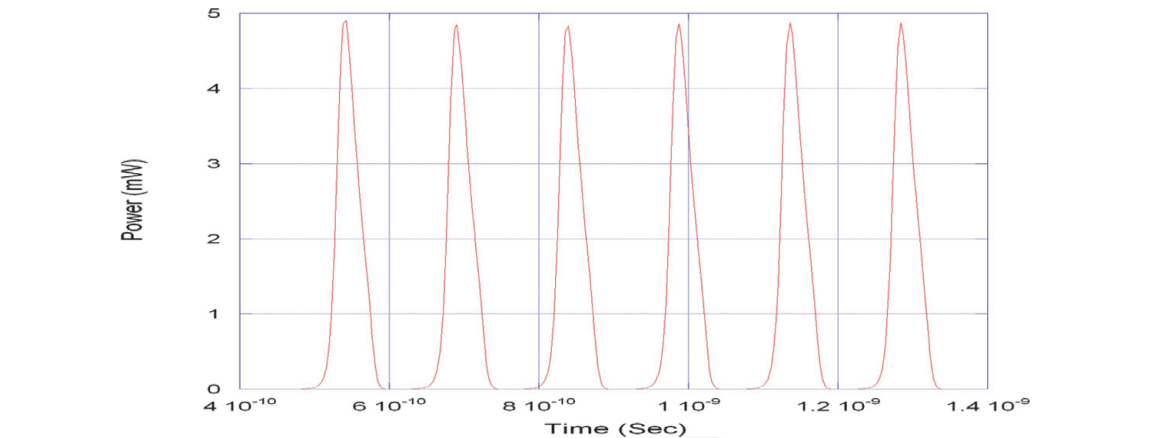


Figure 8. Time domain plot for self-pulsation case (delay = 50 ps, gain = -0.05) for 50 mA bias current where the pulse interval is 147 ps.

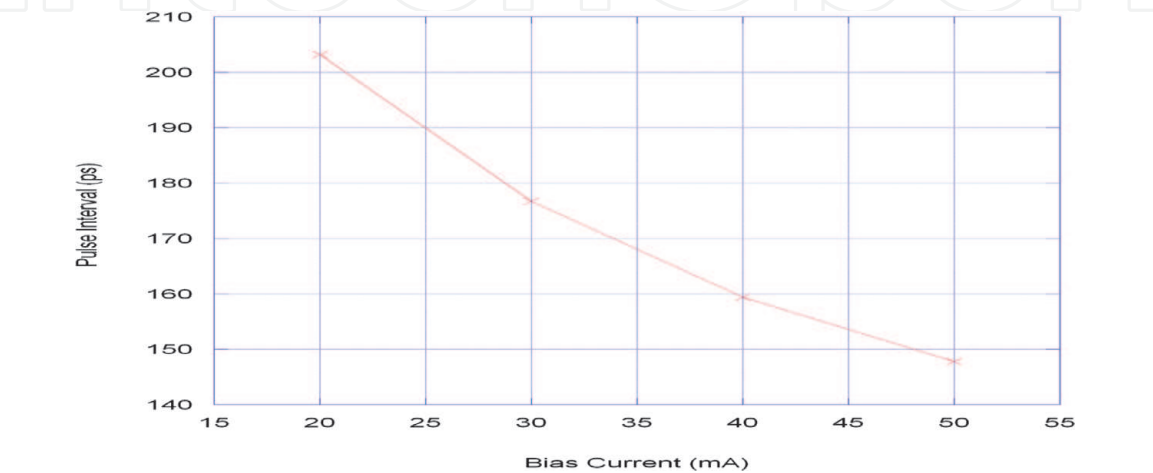


Figure 9. Pulse interval adjustment as a function of bias current for 50 ps delay and gain of -0.05 .

4.1 Pulsed-source noise analysis

In section (2) of this chapter, we analyzed the rate Eqs. (5)–(7) without the inclusion of the Langevin noise terms $F_N(t)$, $F_S(t)$ and $F_\phi(t)$ are the noise terms added respectively to the rate equations. These noise terms are Gaussian random processes with zero mean value under the Markovian assumption (memory-less system) [17]. The Markovian approximation of this correlation function is of the form:

$$\langle F_i(t)F_j(t') \rangle = 2D_{ij}\delta(t - t') \quad (16)$$

Where $i, j = S, N$, or ϕ .

D_{ij} is the diffusion coefficient with full derivation presented in [17].

The other type of noise effect analyzed is the system phase noise, which has dramatic effects on the performance of pulsed laser sources especially when it comes to timing jitter. The system phase noise $L(f)$ is produced from the effect of the laser linewidth $\delta\nu$ and the power spectral density $S_\phi(f)$ of that linewidth.

$$S_\phi(f) = \frac{1}{1 + \frac{2*f}{\delta\nu}} \quad (17)$$

The system phase noise $L(f)$ shown in **Figure 10** is related to the linewidth power spectral density as follow [18]:

$$L(f) = \frac{S_\phi(f)}{2} \quad (18)$$

The integrated rms timing jitter σ_j which represents the upper bound of the timing jitter of the oscillator shown in **Figure 11** is calculated as follow [19].

$$\sigma_j = \frac{\text{Pulse Interval}}{2\pi} \sqrt{2 * \int_{f_{min}}^{f_{max}} L(f) df} \quad (19)$$

Where f_{min} and f_{max} are the boundary of the frequency range.

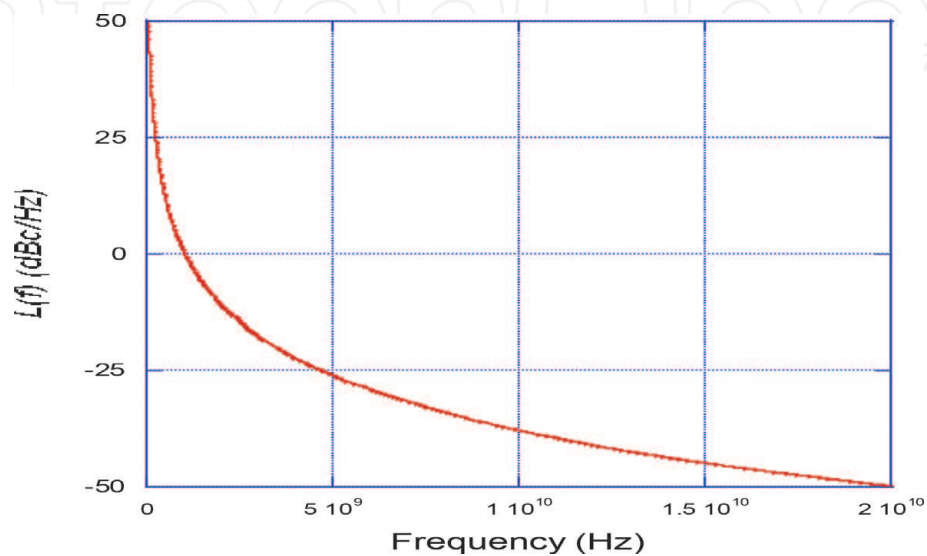


Figure 10.
Laser phase noise plot derived from the spectral density of the line-width.

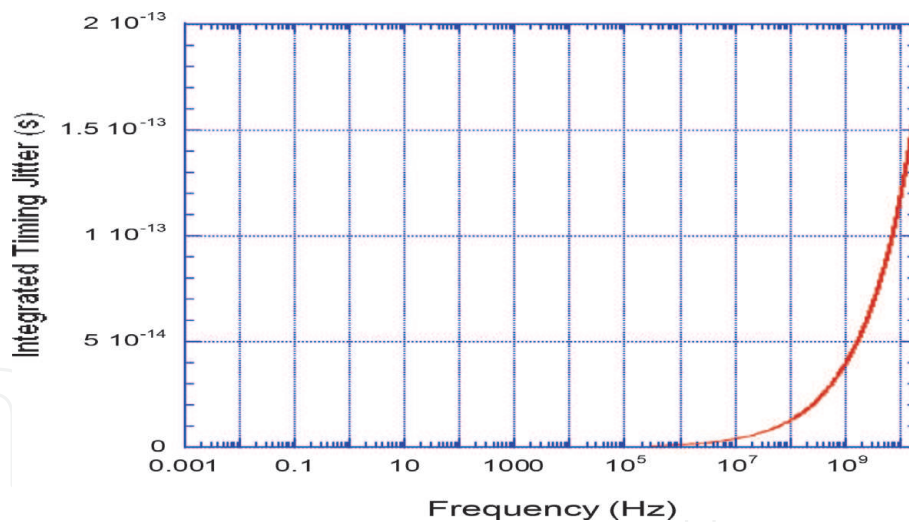


Figure 11.
rms timing jitter over the entire frequency range.

For a pulsed source with a pulse interval of 80 ps, the maximum tolerated rms jitter for sampling application is 120th the pulse interval according to [19]. The listed requirements of maximum tolerated rms jitter is 667 fs while our calculated jitter shown in **Figure 11** is around 15 fs.

We also analyzed how certain laser physical design parameters presented can enhance further the performance of this self-pulsating laser structure with feedback for neuromorphic application. Our analysis determined that increasing the laser cavity length can produce a narrower linewidth by increasing the photon lifetime which will enhance further the timing jitter performance, another approach is to use quantum dot based laser structures which can deliver close to zero or negative linewidth enhancement factor (α parameter).

5. Conclusion

Based on the modified rate equations for analyzing DFB laser system with electronic feedback, this work addresses the need for self-pulsating laser behaving as a photonic neuron, this work provides detailed requirements for feedback loop delay, bandwidth, and gain ranges required to operate the laser self-pulsation modes. These effects were simulated numerically and guidelines were generated for the list of recommended parameters necessary to realize such system. The time domain pulse interval which is crucial for neuromorphic photonics was also analyzed using only the laser drive current for tuning the pulse interval of -2 ps/mA for the realization of variable spaced pulses necessary for this application with pulse spikes as narrow as 30 ps. We also provided analysis of phase noise and rms jitter. These results also show that a pulse train can be generated and controlled with only the laser bias current without the use of external clocking or signaling sources, while PPM signals can ride on top of the laser current modulation to code signals into the laser output, which now provides to degrees of adjustments, one for the pulse grouping (interval) and one for the information to be transmitted using PPM.

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References

- [1] Von Neumann J. IEEE Annals of the History of Computing. 1993;**15**:27
- [2] Sporns O., Networks of the Brain, 1st Edition, ISBN 978-0-262-01469-4 (2011)
- [3] Hasler J et al. Frontiers of Neuroscience. 2013;**7**:118
- [4] Goi E et al. Perspective on photonic memristive neuromorphic computing, PhotoniX journal, springer open, Vol. 1. Issue. 2020:3
- [5] Miscuglio M., et al., Applied Physics Reviews **7**, 031404 (2020)
- [6] Nahmias M et al. IEEE journal of selected topics in quantum electronics, Vol. 19, No. 5. In: 1800212 Sept./Oct. 2013
- [7] Shiu DS et al. IEEE Transactions on Communications. 1999;**47**(8):1201-1210
- [8] Shahine M. H., DFB Laser Diode Dynamics with Optoelectronic Feedback, D. S. Patil, Editor. Semiconductor Laser Diode Technology and Applications, IntechOpen, ISBN 978-953-51-0549-7, Chapter 6, (2012)
- [9] Wan, et al., IEEE custom integrated circuits conference, pp. 25-5-1 (2005)
- [10] He, et al., Analog Integrated Circuit Signal Processing Journal, Vol. 59, pp. 215-221 (2009)
- [11] Xia G et al. IEEE Journal of Lightw. Technol. 2005;**23**(12):4296-4304
- [12] Tang S et al. IEEE Journal of Quantum Electronics. 2001;**37**(3): 329-336
- [13] Lin F et al. IEEE Journal of Quantum Electronics. 2003;**39**(4):562-568
- [14] Shahine MH et al. IEEE Photonics Journal. 2010;**2**(6):1013-1026
- [15] Shahine M. H., Systems and methods for real-time compensation for non-linearity in optical sources for analog signal transmission”, United States Patent 7,505,496, (Mar. 17, 2009)
- [16] Adler R. Proc. IRE Waves Electrons. Jun. 1946;**34**(6):351-357
- [17] Helms J et al. IEEE Journal of Lightwave Technology. 1991;**9**:1567
- [18] Pozar D. M., Microwave and RF Design of Wireless Systems. Hoboken, NJ: Wiley, 2001
- [19] Lasri J et al. Optics Express. Jun. 2003;**11**(12):1430-1435