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DFB Laser Diode Dynamics with Optoelectronic Feedback

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1. Introduction

Semiconductor lasers have been one of the major building blocks of fiber optics based communication systems. For the past two decades, specifications of these lasers have been tailored to specific applications by defining certain performance parameters that do not necessarily overlap from one application to another. In this simulation work, we modify and enhance essential performance parameters of simple, low cost lasers and tailor them to specific applications that normally require advanced and complicated laser structures by using electronic feedback for instantaneous impairment correction, while at the same time maintain a compact size for the laser and the supporting circuitry around it. The main driver behind this work is to facilitate photonic integration by analyzing design cases with specific delays and structures for the feedback loop to deliver as a first step, a comprehensive design study for hybrid integration. Specific applications targeted are, analog transmission for wireless backhauling by reducing the laser Relative Intensity Noise and maintaining and enhancing transmitter linearity, improving laser modulation bandwidth and increasing the laser relaxation oscillation frequency, laser line-width reduction to target long haul transmission and coherent detection and finally producing self-pulsating laser for analog to digital conversion sampling application. The performance for all these applications is analyzed in both time and frequency domains. For the optical sampling source application, the feedback loop needs to be operating outside the stable regime in order for the laser to run in the self-pulsation mode, where the laser drive current can be used as a single point of control for the pulsation rep-rate.

2. Background and motivation

The work for controlling and adjusting semiconductor laser characteristics using electronic feedback was started in the early 1980's (Peterman,1991;Ohtsu,1996;Ohtsu,1988) for both controlling the laser RIN and Line-width. By the mid 1980's, it became clear to researchers that using electronic feedback control scheme would not provide the desired results due to two fundamental limitations in the feedback loops used then (Ohtsubo,2007). The first limitation was the limited bandwidth of the electronic components used in the feedback loop, which was significantly less than the modulation bandwidth of the laser itself and did not provide corrective feedback signal of the laser performance over the entire laser

operational frequency range. The second limitation was large amount of delay that was introduced in the feedback loop by splitting the laser output light from the front facet and using an optical splitter and multistage amplifiers in the feedback chain.

Due to those limitations, the results achieved then were very limited in improving the laser performance and did not provide any significant breakthroughs.

In order to revive this area of research, we have proposed solutions to solve the issues introduced by the two limitations listed above. In the past few years we were able to use wideband back-facet monitors and wideband trans-impedance amplifiers that matched or exceeded the laser bandwidth, we also proposed using the back-facet to tap the laser output power hence reducing the feedback loop delay. By providing solutions to solve these issues, which proved essential to the advancement of photonic integration. Recently, DARPA has started soliciting solutions for the problem statement we specified above (DARPA, 2011). We understand that our work addresses the roadmap for delivering those solutions to DARPA which serves as a validation for reviving this area of research.

In order to address the specific issues of photonic integration, efforts were concentrated in simulations by using certain parameters that are within the acceptable ranges for such integrated solutions (i.e. loop delays between 10ps and 100ps) although, it's not difficult to expand the simulation range beyond these values, addressing this specific integration application is the goal for this chapter.

This study also provides the analysis of the laser as a pulsing source in terms of jitter and noise performance for analog to digital photonic sampling application using DFB laser, which has not been addressed previously and is also part of the DARPA proposal request.

3. Basic control theory

The theory behind this work is based on the classical control theory of negative feedback which has been well known since the pioneering work by H.S. Black who showed that noise of a classical oscillator can be suppressed by negative feedback stabilization (Black, 1934). Recent work by (Wan, 2005), has presented a rigorous, yet simple and intuitive, non-linear analysis method for understanding and predicting injection locking in LC oscillators.

A system with a negative feedback control loop is shown in figure (1).

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), and a subtraction function to produce the difference between the input signal x and the output from the feedback element y.



Fig. 1. Negative Feedback loop system.

Where A(s) represents laser transfer function, B(s) represents 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:

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

This system can be linearized by making the gain product A(s)*B(s) >> 1.

With this condition, the transfer function becomes dependent solely on the feedback gain coefficient and response of the feedback loop which can be made 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 . At least one of the closed-loop poles of an unstable loop will lie in the right half of the s-plane in figure (2). Analysis of stability by investigating pole location can be done by the using the Nyquist criterion which is often used instead of resolving the characteristic equation (He, 2009; Maisel, 1975; Luenberger, 1979). It is based on Nyquist plot that is a plot of real and imaginary parts of open-loop transfer function. If poles are present in the Left Half of the s-Plane, the closed-loop system is stable. In brief, the Nyquist criterion is a method for the determination of the stability of feedback systems as a function of an adjustable gain and delay parameters. It does not provide detailed information concerning the location of the closed-loop poles as a function of *B*(*s*), but rather, simply determines whether or not the system is stable for any specified value of *B*(*s*). On the other hand, the Nyquist criterion can be applied to system functions in which no analytical description of the forward and feedback path system functions is available.



Fig. 2. S-plane plot.

For the RIN and line-width reduction systems work presented later in this chapter, the closed-loop system must to be stable.

In stabilizing an unstable system, the adjustable gain is used to move the poles into the LHP for a continuous-time system. Also the feedback can be used to broaden the bandwidth of a system by moving the pole as to decrease the time constant of the system. Furthermore, just as feedback can be used to relocate the poles to improve system performance, there is the

potential that with an improper choice of feedback parameters, a stable system can be destabilized.

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 is fulfilled. This criterion is based on having the denominator of the closed loop transfer function go to zero. The poles in this self-pulsation mode need to be located 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:

$$\angle T(j\omega) = 0 \Longrightarrow \omega = \omega_0 \tag{3}$$

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

These equations (3) and (4) are referred to as the phase and gain conditions, respectively. According to Barkhausen criterion, the oscillation frequency is determined by the phase condition (3). As the poles move further to the Right Half Plane (RHP) the system becomes unstable and will enter into the chaos mode of operation.

4. Laser optimized for analog signal modulation with stable feedback settings

Transmission of analog optical amplitude modulated signals imposes stringent demands on the linearity of the system. Transmitter non-linearity causes the modulated sub carriers to mix and generate inter-modulation products, which limits the channel capacity (Helms, 1991). In order to directly modulate the laser with an analog signal and expect that the output optical power to represent that signal, the L-I (light vs. Current) relationship has to remain linear over temperature and over the laser lifetime. As stated in (Stephens, 1982; Stubkjair, 1983), that the primary cause of this non-linearity is the laser photon-electron interaction. This problem is not as critical when the laser is modulated with a low frequency signal compared to the ROF (Relaxation Oscillation Frequency) of the laser, since at such low modulation speed, even when the OMD (Optical Modulation Depth) of the signal approach 100%, the laser is virtually in a quasi-steady state as it is ramping up and down along the L-I curve, and consequently the linearity of the modulation response is basically that of a CW light-current characteristic, which is linear. However as the modulation frequency increases and start to approach the ROF of the laser, the harmonic distortions increase very rapidly. The second harmonics of the modulation signal increase roughly as the square of OMD while the IMP (Inter-Modulation Product) increase as the cube of the OMD. Previous works have been successful in producing linear transmitters for analog signals using lasers with external Mach-Zehnder modulator, and insert a linearizer circuitry after the modulator using an optical splitter (Chiu, 1999), There was also the feed-forward technique using two lasers (Ismail, 2004; Ralph, 1999), it was demonstrated recently using two lasers in every transmitter to improve linearization, however these solutions are costly and are not attractive for low cost deployment of systems for wireless backhauling.

A block diagram representing the proposed method is shown in figure (3). Based on this architecture (Shahine, 2009a), a sample of the output beam of the laser is detected through the large bandwidth back-facet monitor. The photocurrent from the back-facet is then amplified and a π phase shifted to produce the negative feedback condition. That signal is

added to the input analog signal to produce the modulating signal of the laser. The overall transfer function of this system is only dependent on the transfer function of the feedback correction loop, when the gain of that loop is large enough. By having a linear transfer function of the feedback loop, the overall transfer function of the system becomes linear. This proposed solution consists of using a back-facet monitor with a wide bandwidth to accommodate the high frequency components of the modulated signal and shortens the feedback loop delay. The Feedback correction loop consists of a trans-impedance amplifier that is connected to an RF combiner, where the input signal is added to the feedback signal. The modeling of this system and the laser are done using the laser rate equations.



Fig. 3. The laser system being modelled.

The dynamic performance of laser diodes is usually analyzed in terms of rate equations (Tomkos, 2001) which add up all physical processes that change the densities of photons and carriers. The carrier density equation is presented in (5), the photon density rate equation is presented in (6) and the optical phase rate equation is presented in (7). These equations were modified to include the feedback loop parameters.

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

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

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

 ρ represents the feedback loop gain, τ represents the feedback loop propagation delay and ω_n represents the 3dB bandwidth of the amplifier circuit.

The Langevin noise terms are the noise terms added respectively to the rate equations. These terms are present due to the carrier generation recombination process, to the spontaneous emission and the generated phase respectively. These noise terms are Gaussian random processes with zero mean value under the Markovian assumption (memory-less system) (Helms, 1991). The Markovian approximation of this correlation function is of the form:

$$\left\langle F_i(t)F_j(t')\right\rangle = 2D_{ij}\delta(t-t') \tag{8}$$

Where $i_{i,j} = S_i N_i$, or ϕ is the diffusion coefficient with full derivation is presented as follows:

$$D_{SS} = \frac{\beta * V_a * N_{sd} * [(V_a * S_{sd}) + 1]^3}{\tau_n}$$
(9)

$$D_{NN} = \frac{V_a * N_{sd}}{\tau_n} [\beta * V_a * S_{sd} + 1]$$
(10)

 $D_{\varphi\varphi} = \frac{R_{sp}}{4 * S} \tag{11}$

Where N_{sd} and S_{sd} represent the steady-state, average values of the carrier and photon populations respectively. R_{sp} is the rate of spontaneous emission.

$$N_{sd} = \frac{1}{\Gamma * \tau_p * g_0} + N_0$$
(12)

$$S_{sd} = \frac{\tau_p}{\tau_n} * N_{sd} * \left(\frac{I}{I_{bias}} - 1\right)$$
(13)

$$R_{SP} = 2 * \Gamma * \sigma_g * (N(t) - N_0)$$
(14)

Where σ_g is the gain cross section, The noise power spectral density $S_{RIN}(f)$ of the laser is of the form:

$$S_{RIN}(f) = \frac{\tau_p * f_r^4 \langle F_N^2 \rangle + \psi^2 * \frac{\langle F_S^2 \rangle}{4 * \pi^2} + \tau_p * f_r^4 * \psi * \frac{\langle F_S F_N \rangle}{\pi} + \frac{\langle F_S^2 \rangle}{4 * \pi} * f^2}{(f^2 - f_r^2) + \psi^2 * f^2}$$
(15)

 $\langle F_s F_N \rangle$ is the cross correlation and is given by:

$$\left\langle F_{S}F_{N}\right\rangle = -\frac{\beta * V_{a} * N_{sd} * (V_{a} * S_{sd} + 1)}{\tau_{n}} + \frac{V_{a} * S_{sd}}{\tau_{p}}$$
(16)

$$\psi = \frac{1}{2 * \pi} \left(\Gamma * g_0 * S_{sd} + \frac{1}{\tau_n} \right)$$
(17)

Where the expression for the RIN with the noise terms included is as follow:

$$RIN = 10 * \log_{10} \frac{S_{RIN}(f)^2}{S_{sd}^2}$$
(18)

Where f_r is the relaxation oscillation frequency of the form:

$$f_r = \frac{1}{2\pi} \sqrt{K - \frac{1}{2} (\gamma_d)^2}$$
(19)

 γ_d is the damping factor:

$$\gamma_d = \frac{1}{\tau_n} + \left[\frac{\Gamma^* g_0}{q^* V_a} (\tau_p + \frac{\varepsilon}{g_0}) (I_{Bias} - I_{th})\right] \left[1 - \frac{\Gamma}{q^* V_a} \right]^* \varepsilon^* \tau_p^* (I_{Bias} - I_{th})$$
(20)

The laser output power is calculated as follows:

$$P(t) = \frac{S(t) * V_a * \eta_0 * h * v}{2 * \Gamma * \tau_p}$$
(21)

After the above description of the laser rate equations including the Langevin noise terms and RIN, Relaxation oscillation frequency and the damping factor. We will go over the description of the laser small signal transfer function which shows under the effect of the feedback on the laser modulation bandwidth, and the changes to the relaxation oscillation frequency and the damping factor.

The laser amplitude modulation response is of the form:

$$H(j\omega) = \frac{K}{[(j\omega)^*(j\omega + \gamma_d)] + K}$$
(22)

Where

$$K = \left[\frac{\Gamma^* g_0}{q^* V_a} (I_{Bias} - I_{th})\right] \left[1 - \frac{\Gamma}{q^* V_a} * \varepsilon * \tau_p (I_{Bias} - I_{th})\right]$$
(23)

For the feedback loop parameters, the amplifier transfer function *A* is of the form:

$$A = \frac{-\rho}{1 + (j\omega / \omega_n)} \tag{24}$$

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

The Feedback loop propagation delay transfer function B is of the form

$$B = \exp(-j\omega\tau)$$

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

Based on the well known control theory of systems with negative feedback (Lax, 1967), the complete transfer function on this complete laser system Y is of the form:

$$Y(j\omega) = \frac{H}{1 + (H * A * B)}$$
(26)

In the case of the feedback effect on laser RIN, the noise spectral density under feedback is of the form:

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(25)

$$S_{RIN-FB}(f) = S_{RIN}(f) * \left| \frac{1}{1 + H * A * B} \right|^2$$
(27)

Based on the parameters listed in table(1) below, the laser threshold current is calculated at 9.4mA and the Bias current range is up to a maximum of 50mA for a well behaved LI curve. The slope efficiency was calculated at 0.04mW/mA.

Symbol	Value	Dimension	Description
I(t)		A	Laser current
S(t)	$\Box G S$	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
3	$3.4x10^{-17}$	cm ³	Gain saturation parameter
$ au_p$	$1.0x10^{-12}$	S	Photon lifetime
β	$4.0x10^{-4}$	-	Spontaneous emission factor
$ au_n$	$3.0x10^{-9}$	S	Carrier lifetime
Va	$9.0x10^{-11}$	cm ³	Volume of the active region
${\Phi}$	-	-	Phase of the electric field from the laser
α	3.1	-	Line-width enhancement factor
P(t)	-	W	Optical power from laser
Q	$1.602 x 10^{-19}$	С	Electronic charge
η	0.1	-	Total quantum efficiency
h	$6.624 x 10^{-34}$	J.s	Plank's constant
ω_n	$75.4x10^9$	Rad/s	3dB Bandwidth of amplifier Circuit
σ_{g}	$2x10^{-20}$	m^2	Gain cross section

Table 1. Laser parameters used in simulations.

4.1 Effects of feedback loop on laser internal parameters

In addition to the analysis that was done in this work in the frequency domain using the feedback control theory and the effect on the total system transfer function in the previous section. We describe in this section the effect of the feedback loop on the rate equations and explain the reasons behind the results we are getting in terms of the changes of the relaxation oscillation frequency and the damping factor. We also explain the effect of this scheme on the laser line-width reduction.

By examining the rate equations presented in the previous section. Looking at equation (5) where we introduced the feedback loop effect. This feedback term in equation (5) actually

reduced the carrier density in the active layer which also reduces the laser current/power slope efficiency and increases the laser threshold current. As shown in figure (4) below. We plotted the carrier density versus the feedback loop gain and as shown, as the feedback loop gain increases, the carrier density decreases.

In addition to N(t) decreasing with the introduction of the feedback loop. N_0 has increased with the introduction of the feedback loop gain of -0.05 from 1.2e18 cm⁻³ to 1.682e18 cm⁻³ which translates to threshold current increase from 9.4mA in the free-running laser to 12.5mA with -0.05 loop gain.



Fig. 4. Carrier density changes with the various feedback loop gain settings where the laser drive current is 50mA and the feedback loop delay is 20ps.



Based on the changes in the carrier density, these changes affect the differential gain (*a*) in the laser as follow:

$$a = \frac{g_0}{\Gamma^* (N(t) - N_0)}$$
(29)

As the carrier density decreases with the introduction of the feedback loop, the differential gain increases. This in-turn affects the relaxation oscillation frequency and the damping factor as follow:

$$f_r = 2 * \pi * \left(\frac{\Gamma * v_g * a}{q * V_a} * \eta * (I_{Bias} - I_{th}) \right)^{1/2}$$
(30)

So as the carrier density decreases, the differential gain increases and that in-turn increases the relaxation oscillation frequency.

Also affected is the phase change of the rate equation below:

$$\frac{d\phi(t)}{dt} = \frac{1}{2}\alpha[\Gamma^* g_0[N(t) - N_0] - \frac{1}{\tau_p}] + F_{\phi}(t)$$
(31)

Where the decrease in the carrier density also decreases the phase fluctuation which in-turn reduces the phase noise and the laser line-width (Agrawal, 1986).

4.2 Simulation results for the analog signal modulation laser system

We first look at the laser modulation response where the relaxation oscillation and the damping factor in the stable regime with very short loop delay will increase when negative feedback is applied due to the reduction of the carrier density. In the case of positive feedback, the ROF and the damping factor actually decrease. The ROF for the system is calculated based on (30) for various input current levels for the free running laser shown in figure (5) which also includes the feedback loop results for stable mode, this figure also shows the enhancement of the relaxation oscillation frequency with the stable feedback parameters that include a very short loopback delay. To maintain stability of the system for analog modulation application, the feedback gain was found to be 0.05 for a maximum feedback loop delay of 20ps.



Fig. 5. Changes in ROF vs. Bias current with (1) no feedback, (2) Stable feedback with short delay and low feedback gain.

Figures (6) and (7) show the magnitude and phase transfer function plots of the system in freerunning laser ($H(j\omega)$) and of the stable feedback ($Y(j\omega)$) modes respectively and they illustrate how much enhancement of the damping factor and modulation bandwidth of the laser can be attained by using negative electronic feedback loop in stable regime where there is close to 50% increase of the modulation bandwidth compared with the free-running laser condition.



Fig. 6. Magnitude and Phase plots of the free-running laser transfer function for various current values.



Fig. 7. Magnitude and Phase plots of the laser transfer function with feedback loop in stable regime for various current values (FB loop gain=-0.05, FB loop delay=20ps).

What was achieved with these results in terms of the shape of the laser modulation response does actually match the recent results by (Feng, 2009) where they fabricated a resonance-free frequency response laser with a fast spontaneous recombination lifetime around 29ps. This complex design was based on transistor laser design where fast recombination lifetime is obtained by a reverse-bias collector field pinning and tilting a dynamic charge population in a thin base, allowing only fast recombination. The tilted-charge laser that was demonstrated with a modulation data-rate of 10 Gb/s which was twice its 3dB bandwidth of 5.6 GHz. More details on this structure complexity in order to achieve similar results to our own results are presented in (Feng, 2009).

There are two fundamental aspects to the system we're proposing for analog signal transmission, the first fundamental goal is to reduce the laser RIN, the second goal is to modify the small signal transfer function of the system as it will become over damped and thus reducing the relaxation oscillation frequency peak which will increase the modulation bandwidth of the system. The flattening of the small-signal modulation response is achieved by introducing the negative feedback loop and maintain the operation of that loop in the stable regime where this stability condition can only be achieved by reducing the feedback loop propagation delay to less than 50ps, for the set feedback loop gain that will remain fixed through-out the operation of that system. For 50mA operating current for the laser, the stability conditions for the feedback loop will be maintained for feedback gain of 0.05 and feedback loop delay of less than 50ps. At 50ps and higher loopback delays, the system starts to self pulsate by operating as an opto-electronic oscillator as we will describe in details in section 5. Figure (8) shows the system magnitude and phase small-signal transfer function for 50mA operating current and various feedback loop delays from 10ps to 100ps where it is evident that the longer the loop delay, the less flat the response becomes and the more peaks are generated in that response.



Fig. 8. Magnitude and Phase plots of the laser transfer function with feedback loop for various feedback loop delays at a fixed current value (FB loop gain=-0.05, laser current=50mA).

Upon further examination of our simulation results, and looking at feedback loop delays between 0ps and 10ps with a finer loop delay increments, the actual system response is shown in figure (9), where reducing the feedback loop delay does not produce a flatter response with the reduced delay, it actually shows that 10ps delay produces a flatter response than all lower loop delays. This behavior is affected by the feedback loop bandwidth value which was set at 12GHz.



Fig. 9. Magnitude and Phase plots of the laser transfer function with feedback loop for various feedback loop delays up to 10ps, with FB loop bandwidth of 12GHz at a fixed current value (FB loop gain=-0.05, laser current=50mA).



Fig. 10. Magnitude and Phase plots of the laser transfer function with feedback loop for feedback loop delay of 0ps, with FB loop bandwidths of 1,2,4,8 and 12GHz at a fixed current value (FB loop gain=-0.05, laser current=50mA).

Reducing the feedback loop bandwidth can reduce the peaking at lower loop delay values as shown in figure (10) where it shows the performance difference at 0ps feedback loop delay between 1,2,4,8 and 12 GHz feedback loop bandwidth settings. The peaking disappear with the lower bandwidth feedback loop, but the consequences of using a lower bandwidth feedback loop than 12GHz actually reduces the stability range that this system operates at on the high end of the loop delay setting, where with the lower bandwidth loop, the self-pulsation actually occurs with loop delay that is far less than the 50ps loop delay we obtain with the 12GHz feedback loop bandwidth, the stability region will be reduced with the lower feedback loop bandwidths to less than 30ps maximum loop delay for system stability and that is not practical for future experimental implementation. Note that at 1GHz bandwidth even with 0ps loop delay, it is shown that self-pulsation can actually occur.



Fig. 11. Magnitude and Phase plots of the laser transfer function with feedback loop for feedback loop delays of 10ps to 100ps, with FB loop bandwidth 12GHz at a fixed current value (FB loop gain=-0.05, laser current=50mA).

Simulation results for laser RIN performance are presented as follow:

First, figure (12) show the laser free-running RIN performance for various drive current settings.



Fig. 12. Laser RIN for various drive current levels (Free-running condition).

When Feedback is applied, the RIN curve is flat and its level drops closer to the ROF in figure (12) which shows the effectiveness of the feedback loop scheme.



Fig. 13. Laser RIN for various drive current levels with the feedback loop applied (Gain=-0.05 and delay=20ps).

The improvement of RIN performance at 50 mA drive current level is 16dB around the ROF level as shown in figure (14).



Fig. 14. Laser RIN at 50mA with and without Feedback applied (Feedback conditions, Gain=-0.05 and delay=20ps).

All the data shown so far have been generated with the laser drive condition based on fixed DC current levels. In the following, we will look at the laser performance when the laser in addition to the DC current drive, will also be modulated with sinusoidal RF signals and what that entails in terms of inter-modulation distortion and CNR.

$$CNR = 10 * \log\left(\frac{m^2}{2 * B * RIN}\right)$$
(32)

Where m is the modulation depth and B is the noise bandwidth.

So based on the RIN reduction results obtained above. For one dB decrease in RIN, a one dB increase in CNR, by getting 16dB decrease in RIN, we can get a 16dB CNR improvement with feedback loop applied.

Finally figure (15) shows the effect of Feedback on eliminating the turn-on ROF in the laser output power in time.



Fig. 15. Laser output power during turn-on where the effect of feedback is shown to eliminate the relaxation oscillation frequency during the power ramp-up.

5. Opto-electronic oscillator for photonic analog to digital conversion

Recent advances in coherent optical communication systems beyond 100Gb/s data rate per channel have increased the bandwidth and speed requirements for the electronic analog to digital conversion (ADC) section of the coherent receiver where the electronic ADC advances are lagging far behind the optical communication data rate growth. A detailed study of the performance of electronic analog to digital converters is presented in (Nazarathy, 1989; Walden, 2008). This review is useful to evaluate the performance requirement for photonic ADCs to achieve significant enhancement over electronic ADC performance. Typically, optics must achieve at least 10 times improvement in bandwidth improvement and/or noise reduction compared to electronics in order for it to be a viable new approach. Based on this, a 1GHz photonic ADC would have to achieve (Effective Number of Bits) ENOB >11, while at 20GHz, ENOB= 4 would be sufficient since this exceeds the comparator ambiguity limit for semiconductor circuits with transition frequency of 150GHz by at least a factor of two (Walden, 2008).

In the area of photonic analog to digital conversion, there has been recent work to address the speed of conversion (Valley, 2007). Most of the work so far has made use of Mode locked lasers (Fiber lasers or quantum dash based lasers) as the optical carrier source for the quantization circuit of the photonic ADC. This has a drawback of lacking tunability control of the pulse interval, cost and laser structure complexity (Bandelow, 2006). Previous work on identifying key photonic source specifications for the photonic ADC is found in (Clark, 1999).

We propose the use of the cost effective and widely available commercial semiconductor DFB laser optimized as a directly modulated laser for 2.5Gb/s data rate by applying

electronic feedback to the laser system to make it suitable as an alternative solution to the mode-locked laser and will meet the performance criteria outlined above for the photonic ADC application. Typical directly modulated laser can be modulated with signal frequency up to its relaxation oscillation frequency (ROF), beyond the ROF, the modulation response decays rapidly (Agrawal, 1986). The laser output when modulated beyond the ROF exhibits period doubling bifurcations with increasing modulation depths.

Our proposed work eliminates the need for external high frequency signal sources, and relies only on DC bias current to generate and tune fast optical pulses using a laser with electronic feedback. The feedback loop delay variation allows us to operate the laser in stable regime with short delay, which smoothes the frequency response of the laser and extends its modulation frequency response capability while increasing the feedback loop delay beyond the stable regime forces the laser to operate in self-pulsation mode.

5.1 Conditions for self-pulsation mode

In analyzing the various configurations of this system, and by applying the FB loop gain of -0.05 and increasing the loop delay to 50ps necessary to produce the self-pulsation state, the process is explained as the sharpening and extraction of the first spike of the ROF. 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 (16) and compare those to the free-running laser transfer function ($H(j\omega)$) magnitude and phase plots for various current and delay values. 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 (16) which indicates the generation of sharp pulsation. The inverse of the frequency peak corresponds to the pulse interval in the time domain.



Fig. 16. 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=50ps).

During this self-pulsation mode, figure (17) shows at 50mA bias current with feedback delay of 50ps and feedback gain of -0.05. The time domain plot of the output power of the system where the pulse interval is 147ps and the pulse width is 50ps.



Fig. 17. Time domain plot for self-pulsation case (delay=50ps, Gain=-0.05) for 50mA bias current where the pulse interval is 147ps.

Figure (18) shows the pulse interval as a function of the bias current where the pulse interval can be fine tuned over a range > 50ps for the specified current range. The shortest pulse interval was achieved for this particular laser when setting the delay at 30ps and the gain at -0.05 with 50mA bias current was 80ps with pulse width of 30ps. These limitations on the pulse width are governed by mainly the laser carrier life-time among other physical parameters of the laser structure.



Fig. 18. Pulse interval adjustment as a function of bias current for 50ps delay and gain of -0.05.

5.2 Sampling source for photonic ADC

We propose the solution in figure (19) as an alternative to the mode-locked fiber lasers presently used in most photonic ADC applications, our proposed source has numerous advantages including lower cost, availability, tunability and most of all size and power dissipation advantage for photonic integration (Shahine, 2010). The disadvantage is that it has a larger pulse width compared to mode-locked lasers but this effect can be reduced by propagating these pulses through dispersion compensating element to match the mode-locked laser performance. This solution consists of one laser system (laser1) operating in the self-pulsating mode with feedback loop Delay=30ps and Gain= -0.05 at 50mA Bias current which would generate the lowest pulse interval at 80ps. The second laser system (laser2) is operating in the stable regime with feedback delay=15ps and Gain=-0.02 which allows the system bandwidth to increase so it would accommodate modulating the signal transferred from the first laser system feedback amplifier. Laser1 system operating in self-pulsation mode, generate the pulses which directly modulate laser2 from the non-inverting output of the feedback amplifier of laser1, modulating laser2 which is optimized with its feedback loop to accommodate fast pulse transition for direct modulation.

The SOA (semiconductor optical amplifiers) are used to match the output power levels from both systems so the combined signal would have the same amplitude when interleaving both signal. The Electrical delay adjustment is used to optimize the timing of the two interleaved signals in order to get the lowest pulse interval possible (avoiding pulse overlap).



Fig. 19. Proposed Photonic ADC pulsed source as a sample and hold circuit where laser 1 is operating in the self-pulsed regime while laser 2 is operated in the stable regime and modulated by the signal from the feedback amplifier of laser 1.

Figure (20) shows the output of this system with a pulse interval of 40ps without the need of any external clock or signal sources. This solution sets the sampling rate at 25GHz which is above the 20GHz minimum requirement stated at the beginning of this section.



Time (sec)

Fig. 20. Optical output of the system in figure (19) where the pulse interval is 40ps.

5.3 Sampling source noise effects analysis

In the previous sections, the effects of RIN and phase noise reduction using electronic feedback, were demonstrated by the reduction in the carrier density. Another type of noise effect analyzed is the system phase noise and the effect it has on the timing jitter performance for pulsed sources. The system phase noise L(f) is produced from the effect of the laser line-width δv and the power spectral density $S_{\phi}(f)$ of that line-width. The calculated line-width of this laser spectrum based on 50mA bias current is 2.4MHz (FWHM). The power spectral density of the laser spectrum is calculated based on (Nazarathy, 1989).

$$S_{\phi}(f) = \frac{A}{1 + \left(\frac{2 * f}{\delta \nu}\right)^2}$$
(33)

The system phase noise L(f) shown in figure (21) is related to the line-width power spectral density as follow (Pozar, 2001):

$$L(f) = \frac{S_{\phi}(f)}{f^2} \tag{34}$$



Fig. 21. Laser phase noise plot derived from the spectral density of the line-width.



Fig. 22. rms timing jitter over the entire frequency range.

The integrated rms timing jitter σ_j which represents the upper bound of the timing jitter of the oscillator shown in figure (22) is calculated as follow (Lasri, 2003)

$$\sigma_{j} = \frac{PulseInterval}{2\pi} \sqrt{2 * \int_{f\min}^{f\max} L(f)df}$$
(35)

Where *f min* and *f max* are the boundary of the frequency range. For a pulsed source with a pulse interval of 80ps, the maximum tolerated rms jitter for sampling application is 120th the pulse interval according to (Jiang, 2005) which lists the requirements for such application leading to maximum tolerated rms jitter of 667fs while our calculated jitter shown in figure (22) is around 150fs which is well below the limits required for photonic ADC sampling application. In addition to the compactness of our proposed solution, this performance exceeds fiber laser performance where according to (Chen, 2007). The timing jitter for a fiber laser was 167fs for a pulse interval of 5ns with RIN of -120dB/Hz.

6. Laser line-width reduction with electronic feedback

As was described in the previous sections, when electronic feedback is introduced, the carrier density is reduced which results in phase noise reduction according to equation (31).

In order to further reduce the frequency noise in the low frequencies region (1/f noise) in the laser Frequency transfer function. A Fabry-Perot etalon is used in the feedback loop that will translate frequency changes to amplitude changes and corrects for the frequency fluctuations by modulating the feedback loop current driving the laser as shown in figure (23). Simultaneously, the frequency noise at high frequencies is also reduced when the feedback loop delay is reduced as will be described later to produce a flat laser FM response across the entire laser operating frequency range.



Fig. 23. System for laser line-width reduction.

This technique uses a wide-band direct frequency modulation for semiconductor laser through injection current by reducing the laser line-width, without increasing the laser cavity size (Shahine, 2009b). Furthermore, since the feedback applied to the laser is negative, a high temporal stability of the central frequency and a narrow line-width of its oscillation spectrum can be obtained simply by reducing the FM noise contributing to the line-width enhancement. By using a highly sensitive optical filter (FP Etalon) used as a frequency discriminator to translate the frequency fluctuation of the laser into a power fluctuation signal, and applying a corrective electrical signal back to the laser to tune its frequency so as to counter these optical frequency fluctuations (He, 2009; Maisel, 1975). This frequency locking system essentially transfers the frequency stability of the frequency discriminator to the laser. If the optical frequency discriminator has a low frequency noise in the locking bandwidth, the laser will inherit this low noise and will display a narrower line-width and longer coherence length. The injection current is controlled so that the laser frequency is locked at the frequency of the maximum negative slope of the transmittance curve of the FP etalon, the fluctuation of the power incident onto the detector is due to residual frequency fluctuations under the feedback condition.

The normalized residual FM noise can be defined as a ratio between the power spectral densities of the free-running laser $S_{VFR}(f)$ and of the laser under electronic feedback $S_{VFB}(f)$. This is given by:

$$\frac{S_{\nu FB}(f)}{S_{\nu FR}(f)} = \left|\frac{1}{1+H(f)}\right|^2$$
(36)

Where *H*(*f*) represents the open loop transfer function of the feedback loop where:

$$H(f) = H_L * H_{FP} * A * B$$
(37)

 H_L is the laser frequency modulation response.

*H*_{FP} is the FP Etalon transfer function.

A is the feedback loop amplifier transfer function.

B is the feedback loop delay transfer function.

A and *B* are the same parameters defined and used previously in section 4.

The laser frequency modulation transfer function is of the form (Tucker, 1985):

$$H_{L}(j\omega) = \frac{\eta^{*}h^{*}\nu}{2^{*}q} \left[\frac{1}{\left(\frac{j\omega^{*}\tau_{p}}{g_{0}^{*}S_{0}}\right)^{2} + \left(\frac{j\omega^{*}\varepsilon}{g_{0}}\right) + 1} \right]$$
(38)

This modulation transfer function only includes the carrier effect and not the thermal effect.

The thermal contribution to the FM response of DFB lasers has been studied theoretically and experimentally in (Correc, 1994). The transfer function of the Fabry-Perot Interferometer when operating in the transmission mode is of the form (Ohtsu, 1988):

$$H_{FP}(f) = \frac{3\sqrt{3}}{4 * \Delta v_{FPI}} * \frac{1}{1 + (\frac{j\omega}{\omega_{FPI}})}$$
(39)

112

6.1 Simulation results for the laser line-width reduction application

The free-running laser magnitude and phase FM response for various input drive currents are shown in figures (24 and 25) respectively.



Fig. 24. Free-running laser FM response (magnitude).



Fig. 25. Free-running laser FM response (phase).

By introducing the electronic feedback loop to the laser, the FM response for the system across the frequency range as shown in figures (26 and 27) for drive current value of 50mA and fixed loop gain of 5. The loop delay was varied from 10ps to 500ps which shows that the desired flat response is obtained with short delay of 10ps. This flat response is ideal for frequency modulation (Alexander, 1989; Gimlett, 1987; Iwashita, 1986).



Fig. 26. Magnitude FM response with FB Gain=-5 and variable loop delay.



Fig. 27. Phase FM response with FB Gain=-5 and variable loop delay.

The power spectral density of the FM noise for the free-running laser can be approximated as follow (Nazarathy, 1989):

$$S_{\nu FR}(f) = \frac{A}{1 + \left(\frac{2 * f}{\delta \nu_{FR}}\right)^2}$$
(40)

Where the laser line-width, of the free-running laser with 50mA bias current is 2.4MHz.

A is a constant related to the Schawlow-Townes parameter.

By applying the feedback loop to reduce the laser line-width, with fixed loop delay of 10ps, we varied the loop gain from 5 to 1000 and shown that the PSD of the FM noise of the system with the feedback loop applied is shown in Figure (28) based on equation (41).

Where $S_{VFB}(f)$ is defined as:

$$S_{\nu FB}(f) = S_{\nu FR}(f) * \left| \frac{1}{1 + H(f)} \right|^2$$
(41)

The effectiveness of this scheme to reduce the laser line-width is calculated based on equation (41) which shows that a 1e5 reduction in PSD FM noise can be achieved with this scheme where the ratio of the FM noise power Spectral density with feedback to the free-running condition is plotted in figure (28).



Fig. 28. PSD of FM noise for laser with FB at 50mA bias current with loop delay of 10ps and various feedback loop gain values, also shown the laser free-running PSD.

7. Conclusion

This chapter discussed the technique of electronic feedback to correct for laser impairments. By shortening the feedback loop delay and widening the feedback loop bandwidth, the laser characteristics fundamentally change and can result in far better device performance.

The simulation study that was done to optimize the design parameters of the feedback loop characteristics, in order to provide a clear roadmap for the implementation of photonic hybrid integration solutions that repair most known impairments in lasers for various applications.

This work provided detailed simulation results to improve the laser performance for analog optical signal transmission including linearization of the output power versus drive current and improve RIN performance by 15dB. It also improved the laser modulation bandwidth by 50% in increasing the relaxation oscillation frequency and increasing the damping rate.

The introduction of the FP etalon to the feedback loop as a frequency to amplitude signal translator provided a solution for reducing the laser line-width from 2.4 MHz to 24 Hz through simulation and the flattening of the laser FM response across the entire frequency range of the laser. These results showed the optimization of the laser for FM modulation and simultaneously reducing the 1/f noise at low frequencies and the carrier effect noise at high frequencies which was achieved by reducing the feedback loop delay.

We also analyzed the performance of laser with electronic feedback loop as an optoelectronic oscillator when the feedback loop was operating outside its stable regime. This work has provided a detailed analysis on how to command such oscillator by tuning the laser drive current. This analysis also covered the performance metrics of the opto-electronic oscillator including jitter performance and phase noise as compared to existing solutions.

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9. References

Agrawal ; Dutta. (1986). Long Wavelength Semiconductor lasers. *Book,Springer, first edition,* 1986

- Alexander, S. et al. (1989). Passive Equalization of semiconductor diode laser frequency Modulation. *IEEE J. of Lightwave Technology*, Vol. 7, (1989) pp. 11-23
- Black, H.S.,(1934) Elec. Eng., Vol.53, (1934) pp. 114

Chiu, Y., et al.(1999) Photonic Technology letters, Vol. 11 (1999), pp. 48

Correc, et. Al., (1994), IEEE journal of Quantum Electronics, Vol. 30, No. 11, (1994), pp. 2485

- Clark, T. R. et al.(1999), Performance of a time and wavelength-interleaved photonic sampler for analog-digital conversion. *IEEE Photonics Technology letters*, Vol. 11,(1999), pp. 1168-1170
- Chen, J. et al.(2007), High repetition rate, low jitter, low intensity noise Er-fiber Laser, *Optics letters*, Vol. 32, No. 11, (2007) pp. 1566-1568.

116

DFB Laser Diode Dynamics with Optoelectronic Feedback

- DARPA-BAA-11-45, (2011), Electronic-photonic heterogeneous integration (E-PHI), April 14, 2011
- Feng, M. et al. (2009), Resonance-Free Frequency Response of a semiconductor laser, *Applied Physics Letters*, Vol. 95, (2009) pp. 033509.
- Gimlett, J. L. et al., (1987). A 2Gb/s Optical FSK Heterodyne transmission experiment using a 1520nm DFB laser. *IEEE Journal of Lightwave Technology*. Vol. 5, (1987) pp. 1315-1324
- He, et. al. (2009) Analog Integrated Circuit Signal Processing Journal (2009) Vol. 59, (2009), pp. 215-221
- Helms, J., et al.(2004), IEEE Journal of Lightwave Technology, Vol. 9 (1991), pp. 1567
- Ismail, T., et. al.(2004) Proc of Optical Fiber Communications Conference, (OFC 2004)- FE3
- Iwashita, et al. (1986). 400Mb/s optical FSK transmission experiment over 270Km of single mode fiber. *IEEE Electronics Letters*, Vol. 22, (1986) pp. 164-165
- Jiang, L. et al.(2005). Semiconductor mode-locked lasers as pulse sources for high bit rate data transmission. *Journal of Optical Fiber Commun.* Rep. 2, (2005). pp. 1-31
- Lasri, J. et al. (2003) Self-starting optoelectronic oscillator for generating ultra-low-jitter high-rate optical pulses. *Optics Express*, Vol. 11, No. 12, (2003) pp. 1430-1435.
- Lax, (1967). Phys. Rev. Vol. 160, (1967), pp. 290
- Luenberger, D.,(1979). Introduction to Dynamic Systems. Wiley Books,(1979), Chapter 5 Maisel,(1975), IEEE transactions on Industrial Electronics and Control Instr., Vol. 22, No. 2, (1975) pp. 122
- Nazarathy, M. et al. (1989). Spectral analysis of optical mixing measurements. *IEEE J. Lightwave Technology*, Vol. 7, No. 7, (1989) pp. 1083-1096.
- Ohtsu,(1996), Frequency control of SCL, Book, Wiley, (1996)
- Ohtsu, (1988), IEEE Journal of Lightwave technology, Vol. 6, (1988), pp. 357
- Ohtsubo J.(2007). Semiconductor lasers, Stability, Instability and Chaos. *second Edition*, *Springer Books*, (2007)
- Peterman, K. (1991). Laser Diode Modulation and Noise. *KluwerAcademic Publishers* (1991)
- Pozar, D. M., (2001). Microwave and RF Design of Wireless Systems., *Book, John Wiley & Sons, Inc.*, (2001).
- Ralph, T. C. et. al.(1999). Optical and Quantum Electronics Journal, Vol. 31,(1999), pp. 583
- Shahine, M. H.,(2009a). 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)
- Shahine, M. H.,(2009b). Semiconductor laser utilizing real-time line-width reduction method. *United States Patent* 7,620,081, (Nov. 17, 2009)
- Shahine, M. H.; Chen, Yung Jui. (2010). Analysis for commanding the self-pulsation of DFB Laser diode with electronic feedback for photonic analog to digital conversion application. *IEEE Photonics Journal*, Vol. 2, No. 6, (2010).pp. 1013-1026
- Stephens, W.E, et al. (1982) IEEE NTC , (1982), pp. F4.3-1
- Stubkjair, K., et al. (1983). IEEE Journal of Quantum Electronics, Vol.16, (1983), pp. 531
- Tomkos, et al.(2001). Extraction of laser rate equations parameters for metro networks.*Optics Communications*, Vol. 194, (2001), pp. 109-129
- Tucker, (1985). IEEE transactions on Electron Devices, Vol. 32, No.12, (1985), pp. 2572
- Valley, G.C., (2007). Photonic analog to digital converters. *Optics Express*, Vol. 15, No. 5, (2007), pp. 1955-1982

Walden, R. H.,(1999). Analog to digital converter survey and analysis. *IEEE Journal of Selected areas in Communications*, Vol.17, (1999), pp. 539-550

Walden, R.H., (2008). Analog-to-digital conversion in the early 21st century. *Book, Wiley Encyclopedia of CS and Engineering* (2008).

Wan, et al. (2005). IEEE custom integrated circuits conference, (2005), pp. 25-5-1







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This book represents a unique collection of the latest developments in the rapidly developing world of semiconductor laser diode technology and applications. An international group of distinguished contributors have covered particular aspects and the book includes optimization of semiconductor laser diode parameters for fascinating applications. This collection of chapters will be of considerable interest to engineers, scientists, technologists and physicists working in research and development in the field of semiconductor laser diode, as well as to young researchers who are at the beginning of their career.

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