ADAPTIVE DIGITAL PREDISTORTION OF LASER DIODE NONLINEARITY FOR WIRELESS APPLICATIONS

Satheesan Nadarajah , Xavier N. Fernando, Reza Sedaghat,
Department of Electrical and Electronic Engineering, Ryerson University
snadaraj@ee.ryerson.ca, xavier@ieee.org, rsedagha@ee.ryerson.ca

Abstract

Nonlinearity of a directly modulated laser diode imposes limitations in the performance of fiber based wireless access schemes. Previously, laser diode nonlinearity has been investigated in CATV related applications. In the CATV scenario, analog opto-electronic compensation schemes have been widely attempted due to the analog nature modulating signals. However, fiber based wireless schemes provide a unique opportunity for digital compensation. In this scenario, although the modulating signal is analog radio signal at several GHz, the information is conveyed through baseband digital symbols that have few Mbps bit rate. The nonlinear distortion of the laser, therefore, reflects on the amplitude and phase distortion of these vector modulated baseband information sequence and, correcting these distortions at baseband symbol rate is adequate. This fact is used in this paper to attempt an adaptive digital predistortion for wireless applications.

Keywords: *Radio-over-fiber, Fiber Wireless, digital predistortion, nonlinear distortion and laser diode nonlinearity*

1. INTRODUCTION

The Radio-over-fiber (ROF) links in wireless access suffer from performance degradation due to optical transmitter nonlinearity. Semiconductor laser diode (LD) nonlinearity generates distortions of inband, harmonic and inter-modulation in modulating (RF) signals. Modulation techniques such as multilevel Quadrature Amplitude Modulation (QAM) are of greater interest for future mobile communication systems because of their high spectral efficiency. In QAM, the baseband information is transmitted by modulating both amplitude and phase of the carrier [1] . This makes such a modulation technique highly sensitive to the LD nonlinearity.

Predistortion is an effective and interesting solution to linearize the LD. This linearization method predistorts the input signal such that the amplitude and phase nonlinearity of the LD are compensated [1]. The predistorter has a non-linear transfer function with gain expansion that is the inverse of the LD gain compression, and a phase rotation that is negative of the LD phase rotation [2]. This prudent method can be implemented at the baseband, IF or RF stage. Baseband predistortion is preferred over others due to lower clock speed requirement of the signal processors.

A detailed study has been performed on the linearization of LDs. As a result, various linearization methods such as Negative Feedback, Optical Feedforward, Quasi-Optical Feedforward and Phase Shift have been proposed. Nevertheless, they involve with complex opto-electronic circuits and device dependent [3] . Adaptive digital predistortion technique seems to be a promising approach, since it is simple and cost effective. This approach is re-programmable, device independent and can track variations of device parameters.

The predistortion can be performed in analog or digital form. This paper presents the adaptive baseband digital predistortion method for linearizing the LD. It provides a greater degree of precision when computing the predistortion coefficients, and there is no concern for stability [2] . In addition, the wireless communications baseband data rate of 2Mbits/s, and the lower clock speed requirement of signal processors makes digital predistortion implementation at the baseband level an excellent choice for fiber based wireless schemes.

2. BACKGROUND

The transfer characteristic of a LD is shown in Fig. 1. This curve applies for direct modulation of the LD.

A proper operating bias point must be chosen in linear region for precise RF signal transfer into the optical domain. In other words, the modulation must take place in linear region for analog signals. If the bias point is not set properly the modulating (RF) signal's optical output might get clipped at the bottom or/and compressed at the top. This will produce distorted RF signal at the receiver, which could undermine the ROF link performance.

CCECE 2003 – CCGEI 2003, Montreal, May/mai 2003

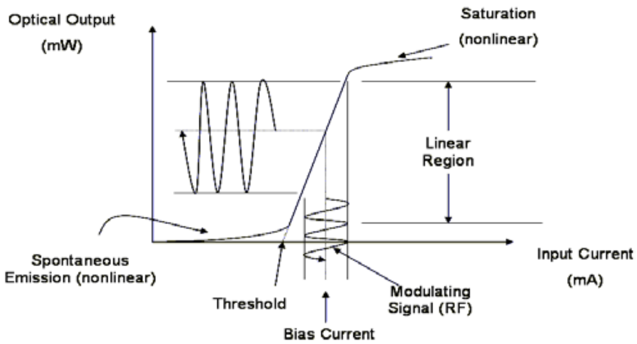

Fig. 1 : Laser Diode Transfer Characteristic

Laser Diode nonlinearity can vary due to temperature variations, internal parameters, parasitics and improper modulation. Laser diodes are highly sensitive to temperature variations. An increase in temperature will increase the threshold current and brings a drop in output power. Moreover, the laser cavity dominant resonant frequency can get lowered resulting in the reduction of modulation bandwidth of RF signals. In essence, the laser cavity becomes very unstable in the event of a temperature rise.

Besides the temperature rise varying the laser diode nonlinearity, the leakage current and axial hole burning can also vary the nonlinearity. The leakage current increases with injected current and with temperature rise. The axial hole burning is an effect that occurs due to non-uniform optical power density along the length of the laser diode cavity [4] . There are numerous other factors like mirror reflectivity that can make the laser diode nonlinear.

The laser diode nonlinearity has been categorized into static and dynamic [4] . The static nonlinearity is studied through the use of a third order polynomial equation, which is given below

$$P_{optical}(t) = P_o[1 + ms(t) + A_2 m^2 s^2(t) + A_3 m^3 s^3(t)] \qquad (1)$$

where $s(t)$ is input electrical signal, P_o is average optical power, m is optical modulation index, A_2 and A_3 are device dependent non-linearity coefficients.

The dynamic non-linearity is studied through the use of well-known laser rate equations. It is frequency dependent, but it can be frequency independent if the frequency of operation is atleast five times less than the laser diode resonance frequency. The laser rate equations are given below,

Rate of Change of photons

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}} \qquad (2)$$

Rate of change of electrons

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi \qquad (3)$$

where n is number of electrons, Φ is number of photons, C is Einstein's Coefficient, τ_{ph} is photon lifetime, R_{sp} is rate of spontaneous emission, τ_{sp} is spontaneous recombination lifetime, J is injection current density and, q is the electron charge.

The nonlinearity in LDs generates distortions of inband, harmonic and inter-modulation in RF signals. The proposed digital predistortion method can be used to linearize the device. To reiterate, the principle of predistortion is to create direct proportionality between the input signal and the optical output. Fig. 2 [3] depicts the predistortion principle.

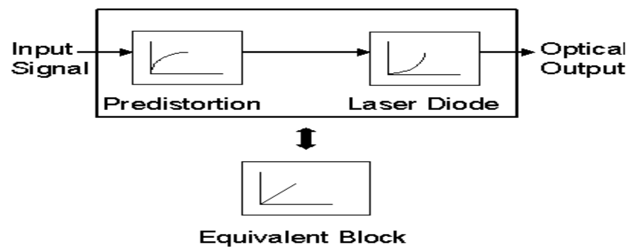

Fig. 2 : The predistortion principle

3. OUR MODEL

To evaluate the performance of predistortion technique on linearization of LDs, the model in Fig. 3 has been implemented using the simulation tool Simulink. In our model, the baseband signal is digital. It is converted to a polar signal by an encoder to realize multilevel Quadrature Amplitude Modulation (QAM). To generate inphase and quadrature components, a serial to parallel converter is used. The inphase and quadrature signals are subject to Raised Cosine Filteration to limit their infinite bandwidth to a finite one. As the next stage is adaptive digital predistortion, both signals are converted to digital form by A/D converters. The adaptive digital predistortion can be performed by employing DSP processors or Application Specific ICs (ASIC). Once the digital predistortion is performed, both signals are converted back to analog form by D/A converters.

The inphase and quadrature signals are then amplitude modulated with 1.8 GHz cosine and sine carrier signals respectively. The modulated signals are then added together to form the multilevel QAM signal. It is this QAM signal that directly modulates the laser diode to generate optical signal for transmission over fiber link. Before modulating an LC network is required to match the 50 Ohms RF line to the approximately 8 Ohms LD.

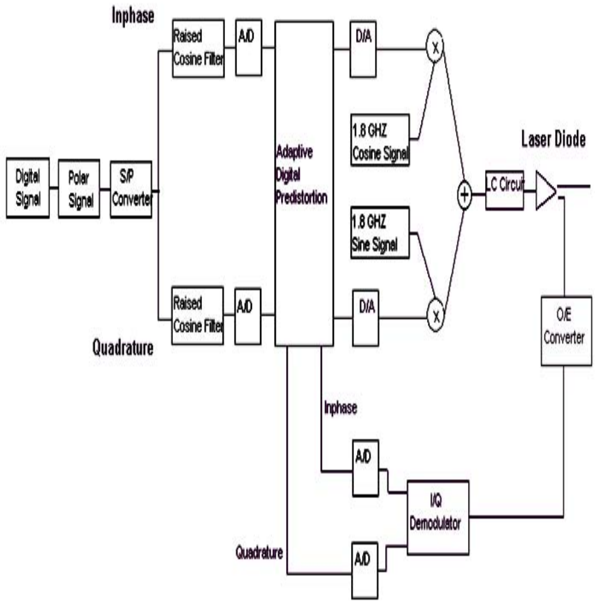

Fig. 3 : Simulation Block Diagram

The feedback loop is formed by O/E Converter, Demodulator, A/D converters, and Adaptation Circuit. For adaptive digital predistortion to take place a copy of the optical output is converted to electrical form by an O/E converter and the electrical signal is then demodulated to generate inphase and quadrature signals. As these signals are needed for generating precise predistortion coefficients they are converted to digital form by an A/D converter. The predistorter then compares the feedback signal with the delayed original signal to generate an error signal, which is used for generating predistortion coefficients. As it reveals, the coefficients are then used to predistort the input signal such that nonlinearity in the LD is removed.

The feedback loop is used only during the training period at which time the predistortion coefficients are updated.

4. RESULTS AND DISCUSSION

The LD is modeled with a simple polynomial equation of $y(t) = s(t) - 0.25\ s^3(t)$. Here, it is assumed that the optical signal is converted into an electrical signal by a linear O/E converter. The *y(t)* is the distorted version of *s(t)* after transmission through the nonlinear device. The second order distortion is not given importance as it is not expected to affect the fundamental signal abruptly and can be removed at the receiver using a filter.

For initial study, a 1 Kbits/s random bit stream is sent in as input to the model. The data rate is observed to be half the source input rate in the inphase and quadrature channels. The inphase channel is modulated with a 1 MHz carrier cosine wave of 1 V amplitude. The quadrature channel is modulated with a 1 MHz carrier sine wave of 1V amplitude. Only 2-ary QAM signal is considered with inphase and quadrature channels having pulse levels of +1 and –1, as it is the initial stage of research work. The generated QAM signal is used to modulate the LD. At the output, the LD nonlinearity generated inband distortion and third order harmonic component.

Fig. 4 shows the phase shift between symbols of the QAM signal and how important it is to linearize the LD to minimize amplitude or phase distortion so that each symbol is identified with ease at the receiver. Fig. 5 shows the QAM signal with third order distortion. A third order distortion is expected to generate inband distortion in the modulating signal and Fig. 6 shows that behavior. A sampling frequency of 6.5 MHz is used for obtaining the spectrum graphs. The inband distortion created by third order distortion is not tolerable in analog over fiber transmission channel, and through digital predistortion this can be minimized to a greater degree. Fig. 7 shows the spectrum of QAM signal, and Fig. 8 shows the effect of third order distortion on the signal. As can be seen the power level has dropped due to inband distortion. In the spectrum graphs, the component in the far right is third harmonic.

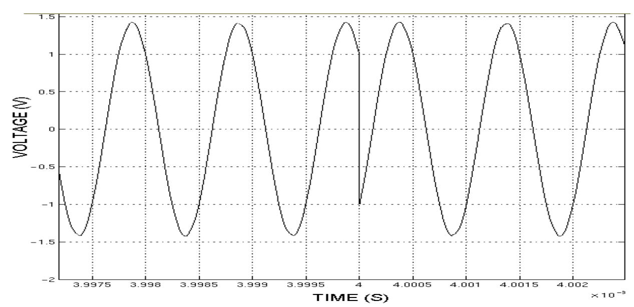

Fig. 4 : QAM signal with phase shift between symbols

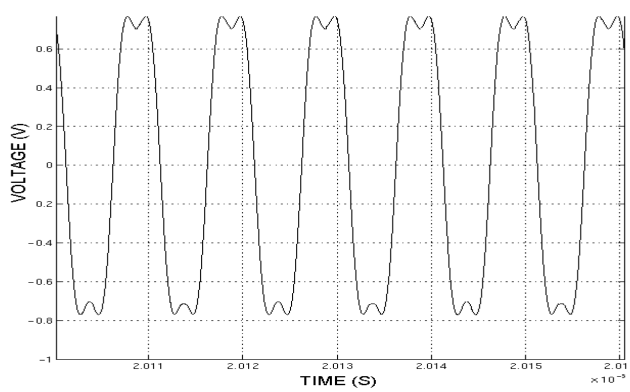

Fig. 5 : QAM signal with third order distortion

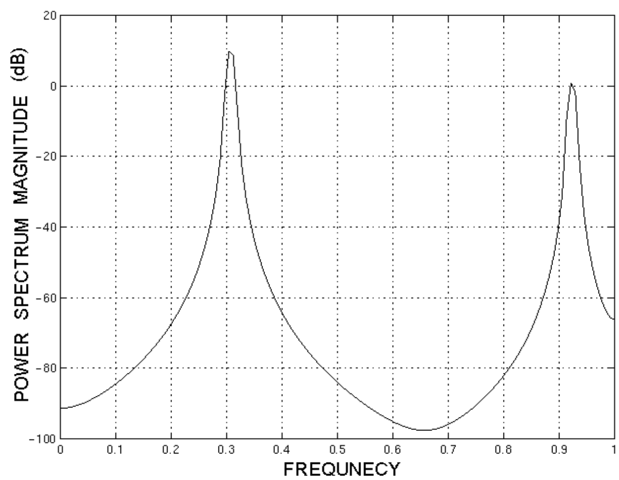

Fig. 6 : Third order distortion components

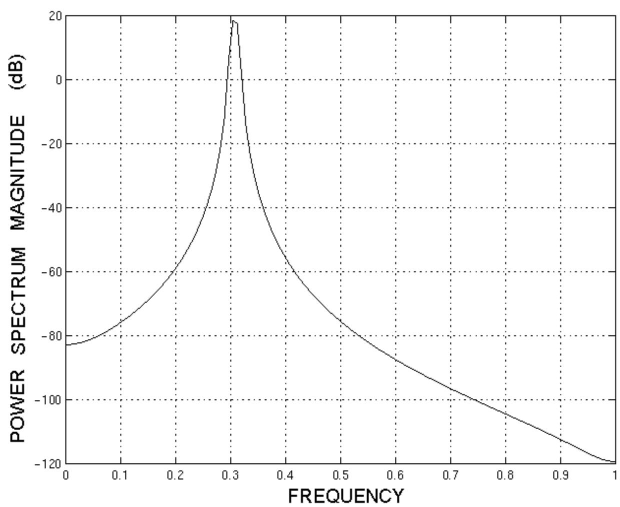

Fig. 7 : QAM signal

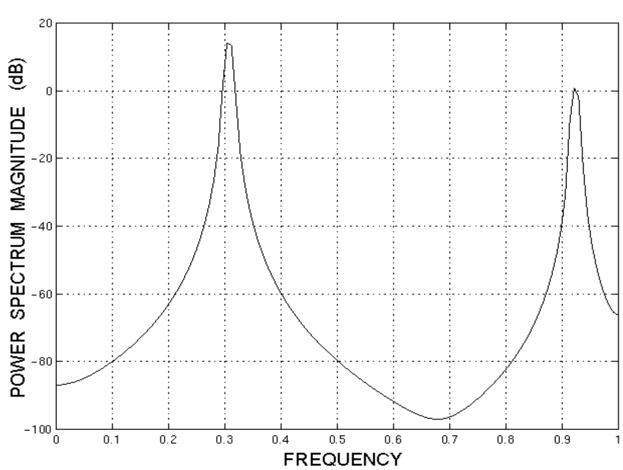

Fig. 8 : QAM signal with third order distortion

5. CONCLUSION

This paper presented the Adaptive Digital Predistortion technique for linearizing semiconductor Laser Diodes. This technique has produced good results in RF power amplifiers. Laser Diodes resemble similar characteristics as RF power amplifiers. The disadvantage in using this technique would be the processors ability to handle the incoming data rate. In our case, the baseband data rate is typically around 2 Mbits/s, a lower clock speed requirement the processor would be able to handle. The adoption of this approach in radio over fiber (ROF) link would well improve the dynamic range of the link.

References

[1] M. Gadheri, S. Kumar, D. E. Dodds, "Adaptive predistortion linearizer using polynomial functions," *IEE Proc.-Common.*, vol. 141, no. 2, pp. 49-55, April 1994

[2] F. Zavosh, M. Thomas, C. Thron, T. Hall, D. Artusi, D. Anderson, D. Ngo, D. Runton, "Digital predistortion techniques for RF Power Amplifiers with CDMA applications," *MICROWAVE JOURNAL,* Horizon House Publications, October 1999

[3] M. Bertelsmeier, W. Zschunke, "Linearization of broadband optical transmission systems by adaptive predistortion," *FREQUENZ*, 38(1984), pp. 206-212

[4] X.N. Fernando, A.B. Sesay, "Adaptive asymmetric linearization of Radio Over Fiber links for wireless access," *Vehicular Technology*, *IEEE Transactions*, vol. 51, issue 6, pp. 1576-1586, November 2002

[5] W.I. Way, "Large signal nonlinear distortion prediction for a single-mode laser diode under microwave intensity modulation*," Journal Lightwave Technology*, vol. LT-5, No.3, pp. 305-315, March 1987