A Novel Linearization Method for Optical Transmitters Based on Directly-Modulated Lasers

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Abstract: A new practical method to correct the non-linearity of directly-modulated lasers is presented and an experimental proof-of-principle demonstration is reported. High-quality NRZ transmission at 16 Gb/s is achieved using a VCSEL specified for 10 Gb/s.

1. Introduction

Optical transmitters based on directly modulated lasers (DMLs) are widely used in optical communication systems. Nowadays, they are the preferred sources for short-reach datacommunication links such as deployed data center and data storage environments owing to their low cost, low complexity and high power efficiency. The ever increasing requirement for high capacity in such systems demands higher line rates in such optical links. However, the high-speed performance of the optical transmitters is limited by the non-linear behavior of the DMLs when operating at baud rates much higher than their 3 dB bandwidth (BW). Common equalization methods such as continuous time linear equalizers (CTLE), feedforward equalizers (FFE) and decision feedback equalizers (DFE) fail to address this issue as they are inherently linear methods. Various methods to correct the laser non-linearity and enable higher transmission rates or larger power margins have been proposed and demonstrated in recent years. These include Volterra series equalizers [1], non-linearity compensation using look-up tables [2, 3], asymmetric FFEs [4, 5] and digital signal processing based on machine learning [6]. However, these methods are too complex and power-hungry to implement in low-cost, energy efficient optical links. They also require some sort of digital signal processing at the transmitter. In this work therefore, we present a novel linearization method of optical transmitters based on directly-modulated lasers that enables the generation of greatly improved output optical waveforms with little residual non-linearity and therefore offering significant improvements in link performance and power budget.

It has been demonstrated that a linear optical output waveform can be obtained from a directly-modulated laser by appropriately shaping the laser modulating current [2]. This ideal current waveform can be back-calculated from the standard laser rate equations for a particular laser source under reasonable assumptions. However, the expression obtained involves terms that are hard to generate in practice. The new method proposed here, named the “Stretched A” method, targets the generation of a good-enough approximation of this ideal modulating current. Through simulations and experiments, it is demonstrated that this approximate current waveform generates an optical output waveform which is very close to the ideal back-calculated one. In addition, our studies show that the modulating current waveform of the “Stretched A” method can be generated with large enough tolerances to render this scheme practical for real-world implementation. Here, we report a proof-of-principle experimental demonstration using an 850 nm multimode VCSEL specified for operation at 10 Gb/s. Data transmission tests are carried out at 16 Gb/s for non-return-to-zero (NRZ) modulation when (i) conventional modulation without any non-linearity correction, (ii) the ideal back-calculated current and (iii) the modulating current obtained through the “Stretched A” method is employed. The obtained optical output waveforms and respective eye diagrams demonstrate that significantly improved signal quality with reduced non-linearity is achieved through the implementation of the proposed method with large tolerances.

2. Stretched A method

The optical output of a laser is proportional to the photon density in the laser cavity. Karar et al. have shown that for a target optical waveform $P(t)$, it is possible to back-calculate from the laser rate equations the electron density $N_e^{bc}(t)$ that produces the desired photon density $N_P(t)$ in the cavity and therefore the target output waveform $P(t)$ [2]. As a result, the ideal back-calculated modulating current $I_{bc}(t)$ can be found and expressed in terms of the laser parameters, the target photon density $N_p(t)$ and its first and second order derivatives $N_p'(t)$ and $N_p''(t)$:

$$I_{bc}(t) = \underbrace{\frac{qV}{\Gamma g_0} \cdot \left(\frac{N_p''}{N_p} - \left(\frac{N_p'}{N_p} \right)^2 + \varepsilon N_p'' \right)}_{I_A} + \underbrace{\frac{qV}{\Gamma} \cdot \left(1 + \frac{\varepsilon}{g_0 \tau_p} + \frac{1 + \varepsilon N_p}{g_0 \tau_e \cdot N_p} \right) \cdot N_p'}_{= I_B} + \underbrace{\frac{qV}{\Gamma \tau_p} \cdot \left(1 + \frac{\varepsilon}{g_0 \tau_e} \right) \cdot N_p}_{= I_C} + \underbrace{\frac{qV}{\tau_e} \cdot \left(N_0 + \frac{1}{\Gamma g_0 \tau_p} \right)}_{= I_D} \quad (1)$$

where q is the electon charge, Γ is the mode confinement factor, β is the spontaneous emission factor, V is the active region volume, τ_e and τ_p are the electron and photon lifetimes respectively, g_0 is the gain slope constant, ε is the gain compression factor and N_0 the carrier density at transparency. $I_{bc}(t)$ can be separated into four components as shown in eq. (1) and which are named I_A, I_B, I_C and I_D. The I_D component includes all constant terms and is equal to the laser threshold, I_C represents the linear terms (proportional to $N_p(t)$), I_B includes terms with $N_p'(t)$ while I_A contains the remaining non-linear terms and those involving $N_p''(t)$. Based on eq. (1), one can calculate the required modulating waveform $I_{bc}(t)$ that produces the desired linear output waveform $P(t)$ for a given laser provided that the laser parameters are either known by design or estimated via measurements. The terms I_A and I_B describe the non-linear response of the laser and if they could be accurately generated, they would correct the non-linear distortions of the output waveform. However, these involve terms such as $1/N_p$ and $(N_p')^2$ which cannot be easily generated in practice. Our proposed "Stretched A" method approximates the ideal I_A and I_B sub-currents with good-enough substitutes I_A^{st} and I_B^{st} which can be generated directly from the derivatives of the linear component $I_C(t)$. This is achieved by (i) omitting the terms in eq. (1) that are least important, (ii) replacing the $1/N_p$ term with the inverse of the average photon density $\overline{N_p}$ in the laser and (iii) appropriately scaling and/or time-shifting the resulting current components. The first and second step lead to eq. (2) while the third results in eq. (3):

$$\widetilde{I_A} = \frac{qV}{\Gamma g_0} \cdot \left(\frac{1}{\overline{N_p}} + \varepsilon\right) \cdot N_p'' = a \cdot b \cdot \frac{d^2 I_C(t)}{dt^2} \quad \text{and} \quad \widetilde{I_B}(t) = \frac{qV}{\Gamma} \cdot N_p' \cdot \left[1 + \frac{\varepsilon}{g_0} \cdot \left(\frac{1}{\tau_p} + \frac{1}{\tau_e}\right)\right] = b\, \frac{dI_C(t)}{dt} \tag{2}$$

$$I_A^{st}(t) = \gamma \cdot \widetilde{I_A}(t + dt) \quad \text{and} \quad I_B^{st}(t) = \delta \cdot \widetilde{I_B}(t) \tag{3}$$

The total modulating current I_{bc}^{st} is obtained by summing up the I_A^{st}, I_B^{st}, I_C and I_D components. The scaling parameters a and b depend on the operating bias point and the laser parameters via eq.(1)- (3). It should be noted that (i) better approximations are obtained for $dt \neq 0$, (ii) the scaling factors γ and δ are ~1 and (iii) in practice the parameters a and b can also be found using adaptive methods. We have already identified several different practical methods to generate the required current components I_A^{st} and I_B^{st} using analog and digital electronics.

3. Simulation results and proof-of-principle demonstration

A low cost 10 Gb/s multimode 850 nm VCSEL is employed for the proof-of-principle demonstration of the "Stretched A" method. The exact device parameters are unknown and therefore light-current (L-I) and S_{21} measurements are carried out. The VCSEL 3 dB BW is found to be ~7 GHz for 5.3 mA bias which is roughly at the middle of the linear region of the L-I curve. The frequency response is fitted using a 3-pole system and hence the estimated intrinsic laser parameters and device parasitics (on-chip and due to electrical connections and packaging) can be extracted. We assume that the parasitic response is linear and therefore can be equalized by common linear pre-distortion methods. However, the laser response is non-linear, for example its frequency response is a function of the modulation current. A standard rate equation model is setup and is used to calculate the optical output for (i) a conventional NRZ modulation, (ii) the ideal I_{bc} (eq. (1)) and (iii) its approximation I_{bc}^{st} (eq. (2) and (3)). In this work, we set that the target output optical waveform for a step input (0→1 transition) to be the convolution of a Gaussian impulse response with a 10% to 90% rise time T_c with the ideal NRZ. This type of response is widely used for modeling and generating test conditions in multimode fibre links. The data rate is assumed to be 16 Gb/s, the target rise time T_c is set to $0.75 \times T$, where T is the symbol period, and PRBS-7 is used as the data pattern. Fig.1 shows the eye diagrams of the output optical waveforms obtained with our rate equation model for the three modulating currents with the values of the eye height h, width w and area $S = w \times h$ noted. It can be clearly noticed that both I_{bc} and I_{bc}^{st} yield improved eye diagrams over the NRZ modulation exhibiting larger h, w and S values, reduced level thickness, skew and jitter. As expected, I_{bc}^{st} provides slightly worse, though still excellent, performance than I_{bc} with some small residual non-linearity observed.

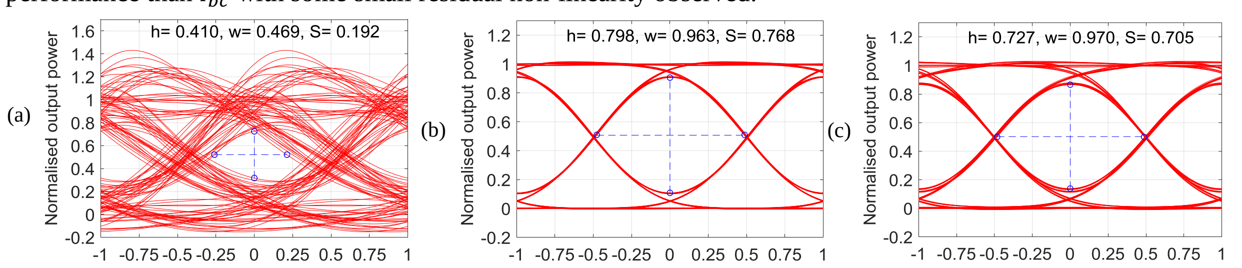

Fig. 1. Simulated eye diagrams at 16 Gb/s for (a) conventional NRZ modulation, (b) the ideal back-calculated modulating current I_{bc} and (c) the approximate current I_{bc}^{st} obtained with the "Stretched A" method ($\gamma = 1.05, dt = 0.1$ UI$, \delta = 1$).

For the experimental demonstration, the same current waveforms are used for the VCSEL modulation. These are pre-distorted to equalize the parasitic frequency response, appropriately sampled (48 GSa/s) and loaded onto an arbitrary waveform generator (AWG) with a 14 GHz analog BW (Tektronix 700001A). For each case, the modulating waveform is amplified to produce an extinction ratio for the output optical waveform of ~5.2 dB and is fed to the laser via a bias tee. The laser is biased at ~5.3 mA. The emitted light is coupled into a standard 50 µm MMF patchcord via a pair of microscope objectives. A variable optical attenuator is used to control the received optical power level. The optical module (80C15, 32 GHz BW) of a sampling oscilloscope (Tektronix DSA8300) is used to record the output optical waveform and eye diagram. Fig. 2 shows the obtained eye diagrams at 16 Gb/s for the three types of modulation for the same received optical power (-1.5 dBm). The experimental eye diagrams exhibit similar shape as the simulated ones and analogous observations can be made regarding the quality of eye diagrams achieved with each method.

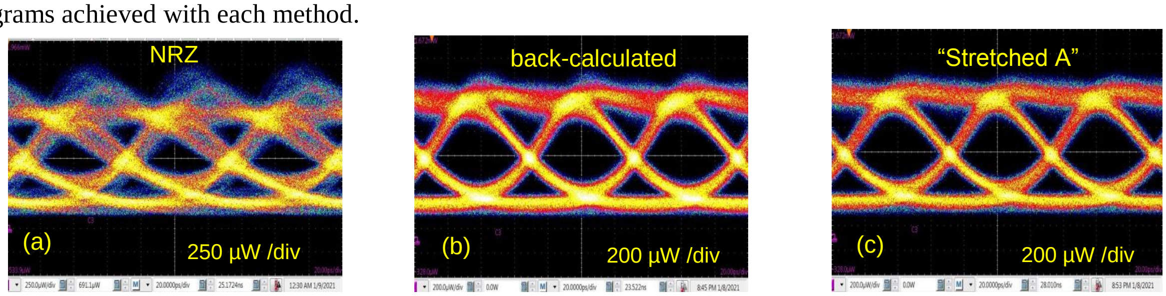

Fig. 2. Recorded eye diagrams at 16 Gb/s for (a) conventional NRZ modulation, (b) the ideal back-calculated modulating current I_{bc} and (c) the approximate current I_{bc}^{st} obtained with the "Stretched A" method ($\gamma = 1.05, dt = 0.1$ UI, $\delta = 1$). Time scale: 20 ps/div.

The received waveforms are recorded and an 11-tap T-spaced FFE is applied offline at the receiver to equalize linear signal distortions. The width w and height h of the eye diagram after the application of the FFE are obtained and used to calculate the eye area, S_{FFE}, for the different modulating currents (Fig. 3a-3c). The results demonstrate that the "Stretched A" method produces an optical output waveform which is very close to that of the ideal back-calculated current. A tolerance analysis is carried out on the I_A^{st}component by varying the γ and dt parameters of eq. (3) and recording the generated output optical waveform. The area, S_{FFE}, of the eye diagram after the application of the FFE at the receiver is obtained for each set of parameters. Fig. 3(d) and (e) show the contour plot of S_{FFE} normalized to its maximum value (γ = 1.05, dt = 0.1 UI, green dot in plots) obtained from the experiments and simulations respectively. Similar variation is observed and large tolerances are demonstrated for both parameters: ±20% for γ and ±0.1 UI for dt.

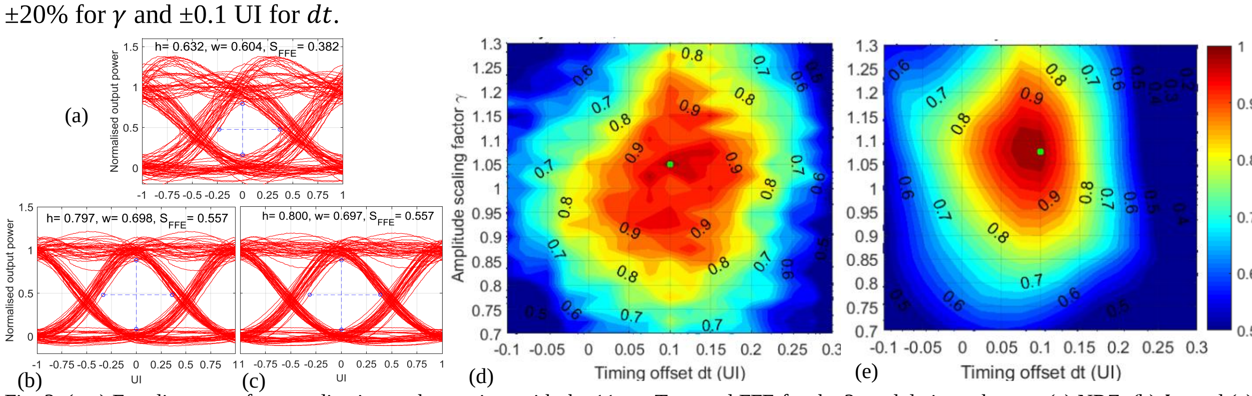

Fig. 3. (a-c) Eye diagrams after equalization at the receiver with the 11-tap T-spaced FFE for the 3 modulation schemes: (a) NRZ, (b) I_{bc} and (c) I_{bc}^{st} and (d-e) normalized eye diagram area S_{FFE} as a function of the I_A^{st} parameters γ and dt obtained via (d) experiments and (e) simulations.

4. Conclusions

A new linearization method for optical transmitters based on DMLs is proposed. It is shown via simulations and experiments that this method enables with large tolerances the generation of optical waveforms with greatly reduced non-linearity. High-quality eye diagrams are obtained for 16 Gb/s transmission with a VCSEL specified for 10 Gb/s.

5. References

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