Laser Diode Chirp Requirements in Wideband Analog Photonic Signal Processing

Farzad Mokhtari-Koushyar, McKay B. Bradford, Monireh Moayedi Pour Fard, Thien-An Nguyen, Sriram Vishwanath
GenXComm Inc., Austin, TX, USA
farzad.mokhtari@genxcomminc.com

Abstract: Distortions added to a 150 MHz OFDM signal in a photonic link comprised of a 4-tap filter and a directly modulated laser is simulated to study the laser chirp impact on the link dynamic range.

1. Introduction

Frequency chirp in laser diodes (LDs) has been traditionally considered the limiting factor of the range in directly modulated (DML) links for digital optical communications [1]. However, due to their inexpensive cost, compact size, high speed, and high linearity, LDs are popular for short and midrange optical links. Thanks to the recent advances in photonic integrated circuit (PIC) fabrication, many analog photonic applications such as optical beam forming, photonic filtering, and in general analog photonic signal processing can be realized on a PIC where the link range is very short. Therefore, a large dynamic range (DR) over a wide range of frequencies should be enabled by directly modulating LDs in these links [2]. In this paper, however, it is demonstrated that chirp will be still the limiting factor even in the short links for analog signal processing.

The wide bandwidth demanded in many microwave photonic (MWP) applications are consumed by multi-subcarrier waveforms such as orthogonal frequency-division multiplexing (OFDM) which suffer from large peak to average power ratio (PAPR) [3, 4]. In fact, dynamic range of the MWP links are usually limited by the nonlinear laser light-current characteristic where the maximum possible optical modulation index (OMI) is used to improve the signal to noise ratio (SNR). Since the phase modulation index of LDs are directly proportional to OMI, the phase of the optical signal will be significantly distorted [5]. Although the links used for analog signal processing can be very short, they are more prone to coherent combinations either as part of the signal processing or as a result of undesired interferences caused by design or fabrication imperfections. Therefore, any interference in the link will translate the phased variations into intensity distortion. Simulation results show depending on the laser linewidth enhancement factor, this phased induced distortion in the link dominates the laser nonlinearities and it can reduce the link dynamic range by more than 20 dB. Here, two case studies are considered and 55 dB of dynamic range over 150 MHz at 1GHz is targeted. Then, traveling-wave time domain (TWTD) simulations are used to calculate the chirp laser requirements to meet the target.

2. Frequency Chirp in Laser Diodes

Modulating the injected current of a laser diode changes the carrier density and temperature in the active region of the laser. So, the effective index of the laser mode will be modulated by the injected current which introduces variations in the instantaneous frequency of the laser, $\Delta\nu(t)$. Due to the large thermal time constant, which is typically in a few microseconds range, thermal chirp frequency is well below the practical modulation frequencies [1]. For an inject current of $I = I_b - I_{th} + I_p i(t)$, the electrical field of the laser output light can be expressed as

$$E(t) = E_0\sqrt{1 + m\, i(t)}e^{j\left(2\pi\nu_0 t+\Delta\phi_c(t)\right)} \qquad (1)$$

where I_b, I_{th}, and I_p are the laser bias current, threshold current, and peak current of the modulation signal accordingly. $i(t)$ is a normalized current where $|i(t)| \leq 1$ and E_0 is field amplitude constant equal to $\sqrt{S_e(I_b - I_{th})}$. S_e is the laser slope efficiency in W/A. $\Delta\phi_c(t)$ represents the phase variation caused by chirp and m is the optical modulation index defined as $m = I_p/(I_b - I_{th})$. The chirp induced by carrier density variation can be written as [1]

$$\Delta\nu_c(t) = \frac{\alpha}{4\pi}\left(\frac{1}{P_0}\frac{dP(t)}{dt} + \frac{\varepsilon}{\tau_p}\Delta P(t)\right) \qquad (2)$$

where $P(t) = P_0 + \Delta P(t)$ is the laser output power. And α, ε, and τ_p are the linewidth enhancement factor, gain suppression factor, and photon lifetime of the laser. The second term in (2) is called adiabatic chirp and typically dominates at frequencies below a few hundred MHz. Therefore, in this paper we only consider the contribution of the first term, transient chirp, as many wideband applications demand higher frequencies than the adiabatic chirp cut-off frequency. Therefore, ignoring the second term in (2), by integrating $\Delta\nu_c(t)$ over time and writing $P(t)$ in terms of the current $\Delta\phi_c(t)$ can be expressed as

$$\Delta\phi_c(t) = \frac{\alpha}{2}(1 + m\, i(t)\,). \qquad (3)$$

In the time varying part of $\Delta\phi_c(t)$, the product of linewidth enhancement factor and OMI determines fluctuations of the phase induced by chirp. While the former is a parameter of the laser, the latter depends on the application. This becomes important specifically in wideband waveforms with a large PAPR such as OFDM which can result in a large OMI to preserve the SNR. $\alpha m/2$ can be interpreted as a phase modulation index. It is noteworthy that the power-current (P-I) characteristic of the laser is assumed perfectly linear here to simply study the distortion caused by chirp. α can be measured by calculating the ratio of intensity to frequency modulation of a laser and usually takes values between 2 to 60 in certain operation condition in quantum-dot lasers [6]. Using the equations provided in this section, the output optical field of the laser is calculated. Then, TWTD simulation is performed to model the signal processing happening through the PIC and eventually photocurrent generation at the PD.

3. Simulation Results

In this section we consider a LD in an MWP link as schematically demonstrated in Fig. 1. The laser is usually followed by an isolator to block external reflections. Also, a polarization controller (PC) helps to align the polarization of the laser light with waveguide of the PIC. The PIC output is received by a photodiode which is connected to a signal analyzer to calculate the spectrum of the signal.

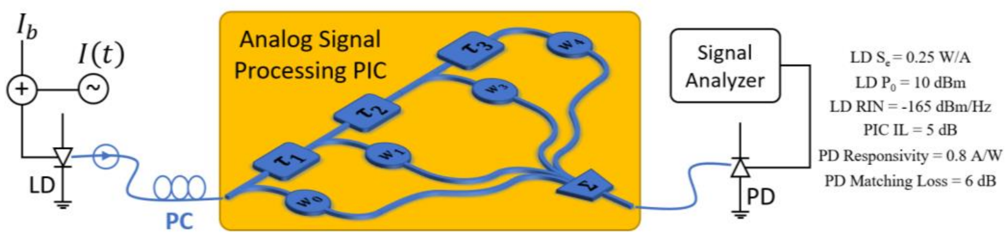

Fig. 1 Schematic of the MWP link for analog signal processing and the parameters used in simulations.

The laser is modulated by an OFDM signal with 150 MHz bandwidth and 1200 subcarriers where an I/Q random bit sequence is mapped on the waveform using 16-QAM modulation scheme. PAPR of the modulated waveform is about 11.4 dB. Adjacent channel power ratio (ACPR) is calculated as a measure of the available DR in the link. The signal power will be determined by the input power and link loss while the adjacent channel power can be dominated by either noise or distortion generated by chirp. It is important to mention that the spectral regrowth seen in the adjacent channels are originated from subcarriers odd-order inter-modulation distortion. For the analog signal processing PIC, a 4-tap filter with 1.625 ns delay between taps and field ratio weights $w = [1, 0.1, 0.1, 0.05]$ are selected. The block shown by $\sum$ in the PIC is where cohere combination happens. This combination can be done using multi-mode interference (MMI) regions, directional couplers, or even photonic lanterns. Each of the mentioned combiners has a different mechanism to add the field, however, for the sake of simplicity we just add the delayed and weighted fields. The rest of the parameters used in the simulation is listed in Fig. 1. The parameters are selected to be practical numbers to make sure the noise calculated at the receiver is a realistic number.
The power spectral density (PSD) of the input OFDM signal with 0 dBm channel power is shown in Fig. 2 (a). With the given tap coefficients and delay for the filter, the output signal is calculated where the LD is biased at $P_0 =$ 10 dBm and $m = 41$ %. As can be seen in Fig.2 (a), the channel power of the output signal is -32 dBm which means 32 dBm link insertion loss (IL). The shallow notch in the PSD of output signal at 1 GHz is coming from the filter response with the given coefficients. The noise at the receiver is limited by PD shot noise which normally means increasing OMI can improve the link SNR, however, the available dynamic range here is limited by distortions. While 54 dB of SNR is available, the chirp induced distortions lead to an ACPR equal to 29.87 dB. Even for an ideal laser source with no chirp, the coherent combination happening during signal processing can generate distortion. To study how laser chirp exacerbates the situation, ACPR is plotted for the same link in Fig. 2 (b) where α is swept from 1 to 8 and OMI is swept from 10 to 70 %. This plot emphasizes the importance of

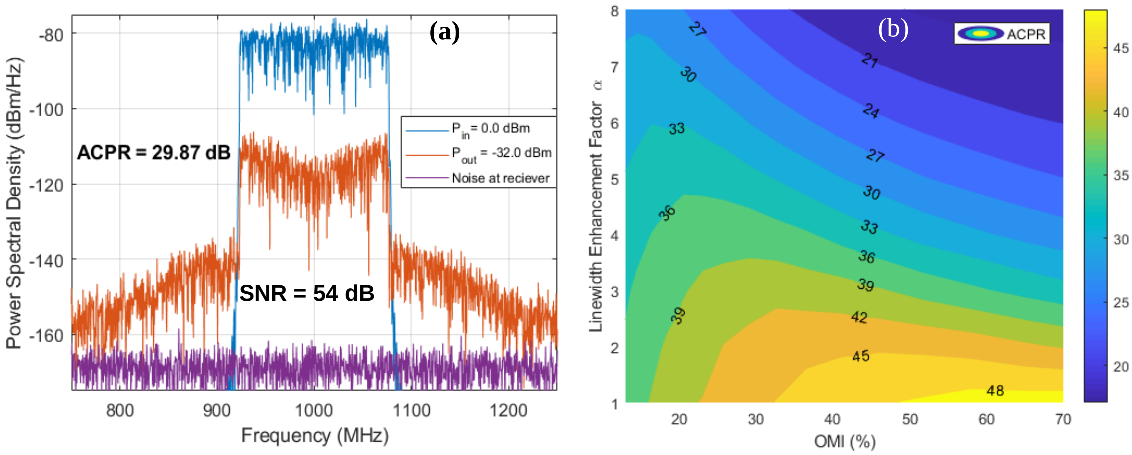

Fig. 2 (a) The power spectral density of input OFDM signal, output signal, and noise at the receiver versus frequency where $\alpha = 5$, $P_0 = 10\ dBm$, and $m = 41\%$. (b) ACPR of the MPW link with given filter coefficients where m and α vary from 10 to 70 % and from 1 to 8, respectively, and $w = [1, 0.1, 0.1, 0.05]$.

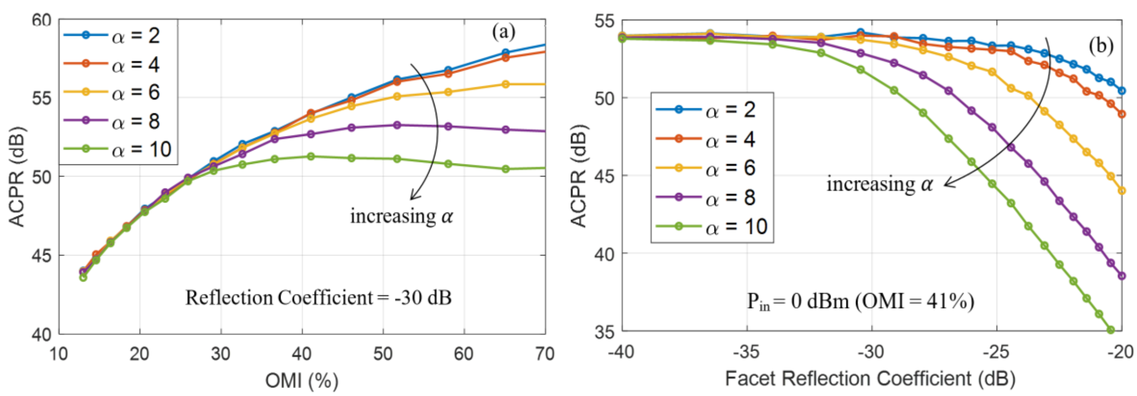

Fig. 3 (a) ACPR versus OMI with $w = [0,0,0,1]$ and -30 dB reflection per facet; and (b) ACPR versus each facet power reflection coefficient where m = 41 % for different values of α.

using a low-chirp laser in DML links. For example, at $m = 30$ %, increasing α from 2.5 to 5 yields a 9 dB ACPR reduction. As OMI increases, for small values of α, ACPR first improves then remains almost constant. However, for larger values of α, boosting OMI immediately results in ACPR reduction which means the distortions are growing at a higher rate than the signal itself.

The interference happening in signal processing can be part of the desired processing or it can be inevitable due to imperfections. For example, the weights of filter $w = [1, 0.1, 0.1, 0.05]$ can be interpreted such as tap 1 is desired while there are -20, -20, and -23 dB leakage from switches in tap 2,3, and 4, respectively. Another scenario of undesired interference is where the filter is set to guide all the light to the last tap, i.e. $w = [0,0,0,1]$, but there are reflections from the input and output facets of the PIC. This will form Fabry-Perot cavity on the PIC which in the presence of the laser chirp introduces distortion as illustrated in Fig. 3 (a). As a result, increasing OMI will not enhance ACPR anymore after some OMI. A laser with larger chirp makes this DR saturation happen at a lower OMI. Fig. 3 (b) shows the link DR will be more sensitive to reflections if a LD with large α is used.

4. References

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