Semi-Analytical Methodology for Advanced Filter Design in Chirped-Managed Lasers

Reza Maram[1,*], Md Samiul Alam[2], Kh Arif Shahriar[2], Pasquale Ricciardi[1], and David V. Plant[2]
[1]*Fonex Data Systems Inc., Montréal, Québec H4S 1P6, Canada*
[2]*Dept. of Electrical and Computer Engineering, McGill University, Montreal, QC H3A 2A7, Canada*
**rmaram@fonex.com*

Abstract: We introduce a novel semi-analytical method for the deterministic design of advanced optical filters in chirped-managed lasers (CMLs), enhancing transmission reach for access networks. This approach can be applied to any baud rate of NRZ and PAM-4, overcoming previous trial-and-error methods. © 2024 The Author(s)

1. Introduction

The performance of a directly modulated laser (DML) in a direct detect system is greatly impaired by its inherent frequency chirp and chromatic dispersion of the optical fiber, limiting both transmission speed and reach. Chirped-managed lasers (CMLs) were introduced as a solution to extend the transmission reach by tailoring the spectrum of the DML using an optical filter (OF) [1]. Recently, several efforts have been made to expand the CML approach to PAM-4 signaling in order to achieve higher throughput [2]. However, to the best of our knowledge, no intuitive filter design procedure has been identified in the literature that explains how CML-based filter designs are achieved, or how the frequency offset (FO) between the OF and the DML spectrum should be determined, often resorting to trial-and-error methods.

In this work, for the first time to the best of our knowledge, we propose a semi-analytical approach to deterministically identify the optimal filter profile and the FO with respect to the signal spectrum, greatly simplifying the optical filter design procedure. This method is applicable for any DMLs with different laser parameters (α, κ), EO bandwidths (EO-BWs) and optical modulation amplitudes (OMAs), as well as various modulation formats to achieve a desired extinction ratio (ER). We present a simulation study of the proposed method for both OOK and PAM-4 formats. We also show that as the modulation speed increases, optical filtering alone may not be sufficient to extend the reach to the access network target of 20 km and efficient digital signal processing (DSP) should be utilized as well. Using a 17 GHz C-band DFB DML and with the aid of a proper optical filter and DSP, we experimentally transmit a 35 Gbaud PAM-4 over 20 km of SSMF at a BER below the HD-FEC threshold of 3.8e-3.

2. CML optical filter design principle and experimental validation

The optical field of a DML can be expressed as $E_{DML}(t) = A_{DML}(t)\, e^{j\varphi_{DML}(t)}$, where $A_{DML}(t)$ is the amplitude and $\varphi_{DML}(t)$ is the phase of the optical field. The frequency chirp of the laser can be described by [3]:

$$\delta f_{DML}(t) = \frac{1}{2\pi}\frac{d\varphi_{DML}(t)}{dt} = \frac{\alpha}{4\pi}\left(\frac{1}{P_{DML}(t)}\frac{dP_{DML}(t)}{dt} + \kappa P_{DML}(t)\right) \quad (1)$$

where $P_{DML}(t) = |A_{DML}(t)|^2$ is the optical power, α is the linewidth enhancement factor (LEF) and κ is adiabatic chirp coefficient. To reduce the negative impact of transient chirp on the transmission distance, one would require a low ER, while for the adiabatic chirp, a large ER would be beneficial. It is not possible to simultaneously satisfy these conditions with a DML alone. The CML approach suggests using a large bias current to minimize the transient chirp for a given OMA, which also leads to a small ER. Then, an optical filter can be used to perform a frequency modulation (FM)-to-amplitude modulation (AM) conversion to enhance the ER [1]. Appropriate OMA value ($\delta f_{adb} = B/2$, δf_{adb} being the FM between the different levels of signal and B being the baud rate) may be used enhance the dispersion tolerance of the CML [1]. In our methodology, we leverage the conventional filter design method for linear and time-invariant (LTI) systems for a fixed DML bias current. The filter transfer function is then identified by:

$$H(f) = E_{CML}(f)/E_{DML}(f) \quad (2)$$

where $E_{DML}(f) = FT\{E_{DML}(t)\}$ is the Fourier transform (FT) of the DML signal and $E_{CML}(f) = FT\{E_{CML}(t)\}$ is the FT of the target signal or CML output signal, $E_{CML}(t) = A_{CML}(t)\, e^{j\varphi_{CML}(t)}$. By understanding the input signal and the desired output signal, we can easily derive the transfer function of the filter for FM-to-AM conversion. We first utilize Eq. (1) and extract the laser parameters (α, κ) by using the small signal response of the DML after fiber transmission and optical spectra of signals with an OMA, as shown in Fig. 1(a). This method gives us the flexibility to independently set and change the chirp parameters. The key part of this filter design is to properly define the target

CML output signal $E_{CML}(t)$. The goal of the CML technique is to increase the ER without causing transient chirp enhancement. In other words, we want to modify the input signal's P_{avg} and OMA, without modifying the frequency chirp or phase, as illustrated in Fig. 1 (b). Thus, $E_{CML}(t)$ should have an $A_{CML}(t)$ which would be a modified version of $A_{DML}(t)$ for a desired ER, provided the energy conservation is not violated, but a similar frequency chirp or phase: $\varphi_{CML}(t) = \varphi_{DML}(t)$.

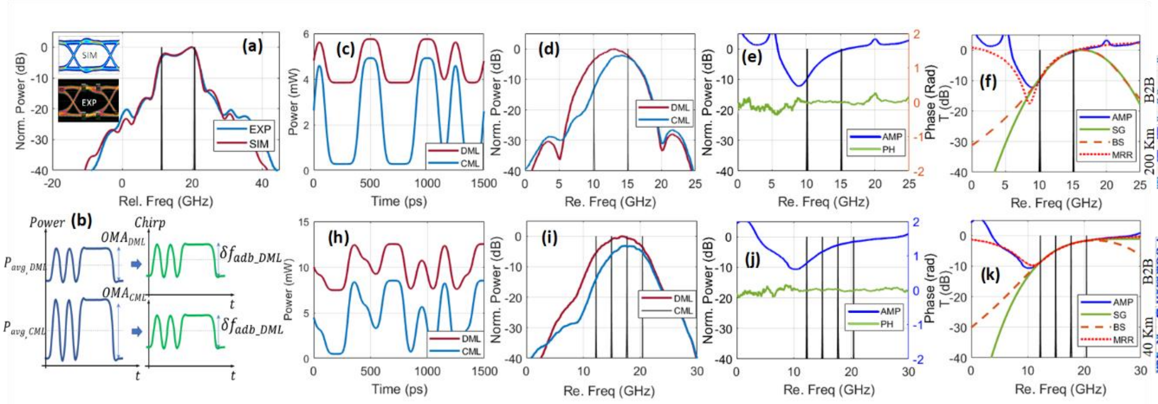

Fig. 1 (a) Measured and simulated optical spectra and eye diagrams for $OMA = 5.2\ mW$. (b) Power and chirp profiles of a DML and a targeted CML output. (c)-(l) Optical filter design methodology and eye-diagrams for (c)-(g) 10 Gbps NRZ and (h)-(l) 10Gbaud PAM-4 CML.

We next explain the filter design procedure using two examples: a 10 Gbps NRZ CML, using the DML parameters used in [4] ($\alpha \approx 3, k \approx 11\ GHz/mW$) to also compare the outcome, and a 10 Gbaud PAM-4 CML using the parameters of the DML available in our lab ($\alpha \approx 4, k \approx 5.25\ GHz/mW$). Figs. 1(c)-(g) and 1(h)-(l) show the results of our analysis for NRZ and PAM-4, respectively. Figs. 1(c) and (h) show the input DMLs (ER $\approx$ 1.5 dB for NRZ and 2.2dB for PAM-4), and the target CMLs with an ER $\approx$ 12 dB. Fig. 1(d) and (i) show the respective power spectra $P_{DML}(f)$ and $P_{CML}(f)$. Having $E_{DML}(f)$ and $E_{CML}(f)$, Fig 1(e) and (j) show the spectral amplitude and phase of the resultant $H(f)$. The effective region of the filter is indeed between the lowest and the highest power level spectra (corresponding to zero and one for NRZ, zero and three for PAM-4), as indicated by black lines. In this region, the filter phase is nearly flat and as expected, the filter's amplitude response is falling from the highest power level spectrum towards the zero spectrum. Figs. 1(f) and (k) depict the subsequent step in the filter design, which is to identify a standard filter profile that aligns well with the amplitude response of $H(f)$ between lowest and highest power level spectra; for this, we employed the Nelder-Mead simplex algorithm. As demonstrated in Fig. 1 (f), for NRZ signaling, a Bessel filter of 3rd order with a 7 GHz BW (very close to that obtained in [3]), a Gaussian filter of 7.11 GHz BW, and a micro ring resonator (MRR) filter with a Q factor of 7281 exhibit a good match with the target filter. The eye-diagrams for B2B, and 200 km using the Bessel filter (Fig. 1(g)) closely match those in [3]. Fig. 1 (k) shows the same filter matching process for the PAM-4 signaling, illustrating three filters that matched well: a 4th order Bessel filter with a BW of ~13.1 GHz, a Super Gaussian (SG) filter with a BW of 27.3 GHz, and an MRR with a Q-factor of 7480. Fig. 1(l) shows the eye-diagrams for B2B, and 40 km fiber propagation using the SG filter.

As inferred from the results in Fig. 1(l), the temporal skew between PAM-4 eyes after propagation becomes the main challenge for multi-level CML signals, potentially limiting the reach. Nonlinear compensation may be necessary to address this issue. To illustrate, we focus on a higher baud rate example of 35 Gbaud DML with an ER of 1.4 dB. As the baud rate increases, selecting the appropriate CML becomes more challenging due to both temporal skew and signal inter-symbol interference (ISI) limitations. Indeed, the spectrum of a PAM-N DML signal can be described as a combination of N sinc functions of $2B$ null-to-null BW, each centered around CW power spectra of different power levels, as illustrated in Fig.2 (a) for PAM-4. To reduce the skew after fiber propagation, selecting a smaller OMA leads to a concentration of different power levels' spectra on both the lower and higher sides of the DML spectrum peak. Utilizing the semi-analytical approach, Fig. 2(b) shows examples of matched filters to achieve ERs of 3-7dB. While the filters can successfully achieve the target ERs, they may also lead to severe ISI for higher ERs, as demonstrated by eye-diagrams of the CML output (B2B) and after 10 km fiber propagation for five different ER values in Fig. 2(c). As a result, to minimize ISI, it may be necessary to limit the target ER as we transition to higher baud rates. In Fig. 2(d)-(f), we present the BER values for different target ERs. The BER vs. fiber propagation distance (L), Fig. 2(d), indicates that an ER of 4-5 dB is optimal for propagation over 10-15 km. However, propagation beyond 15 km is not possible at the HD-FEC threshold due to ISI and pronounced eye skew. This suggests that for longer propagation distance, optical filtering alone is insufficient for high baud rate PAM-4 signals.

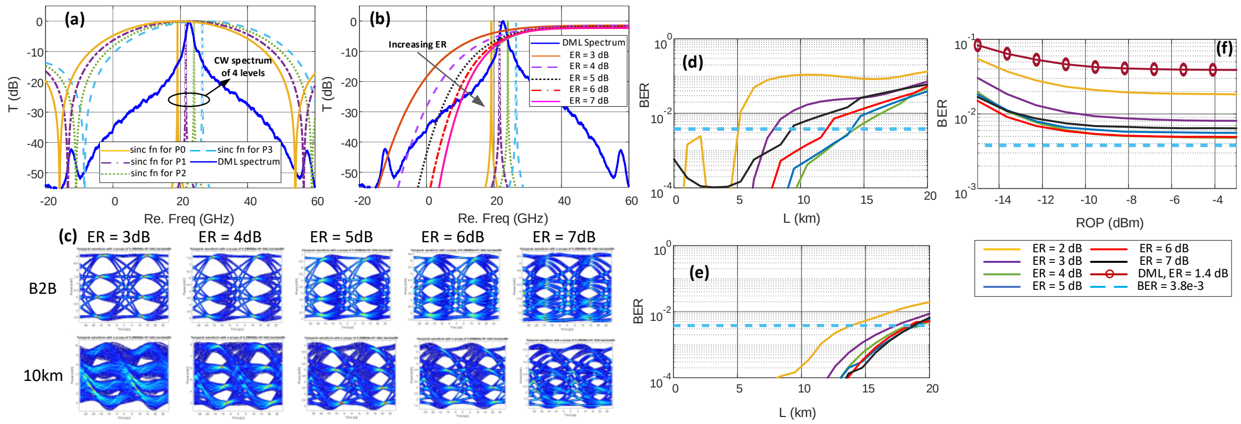

Fig. 2. (a) Sinc functions and CW spectra corresponding to the four levels of a PAM-4 signal. (b) DML spectrum and required OFs for different ERs. (c) Eye diagram at B2B and after 10 km propagation with filters for 35 Gbaud PAM-4 signaling. BER vs. propagation distance for different ERs (d) without and (e) with FFE. (f) BER vs. ROP for different ERs w/ FFE after 20 km fiber.

Therefore, we employ symbol-spaced (1 samples/symbol) linear FFE (9 taps) and examine the BER vs. propagation distance (L) curves shown in Fig. 2(e). With FFE, the propagation distance can be extended up to 18 km. The improvement with FFE is significant for "DML only" case, where receiver equalization extends the reach from 5 km to 14 km. In Fig. 2(f), we plot the BER vs. ROP for 20 km propagation, showing that extending the reach to 20 km with only optical filtering and linear signal processing is not feasible. Non-linear compensation is thus required for longer transmission reach, as discussed in the following part with an experimental demonstration.

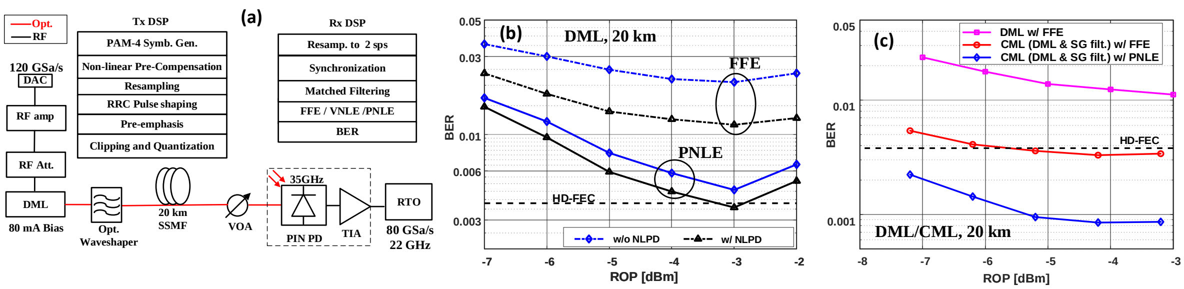

Fig. 3. (a) Experimental setup with employed DSP at the transmitter and receiver. (b) BER vs. ROP after 20 km transmission with (black) and without NLPD (blue) at the transmitter. (c) BEE vs. ROP with a designed SG optical filter for ER of 5dB.

Fig. 3(a) depicts the experimental setup along with the transmitter (Tx) and receiver (Rx) DSP employed to test the C-band DML/CML transmission performance. We focus on 35 Gbaud PAM-4, using the available DML in our lab with an EO-BW of 17 GHz at 80 mA bias current. We keep our analysis limited to 20 km of SSMF transmission to test the impact of optical filtering and DSP. The receiver DSPs are performed at 2 sps and 31 linear filter taps that are used in all cases to equalize the distorted signal before BER calculation. More taps are required in experiment to compensate for the BW limitation, ripples and reflections coming from the long RF chain. We use an optical Waveshaper to realize the designed 2^{nd} order SG filter for an ER of 5dB (Fig. 2(b)), with a BW of ~50 GHz and a FO of ~25 GHz. First, Fig. 3(b) shows the BER vs. ROP for the DML with linear FFE and 2^{nd} order polynomial non-linear equalizer (PNLE) at the receiver with and without nonlinear pre-distortion (NLPD) at the transmitter, compensating partially for the nonlinearity coming from unequal eye-openings and eye-skew after fiber transmission. Next, we plot the BER vs. ROP curves for the designed filter with NLPD applied at the transmitter, as depicted in Fig. 3(c). As can be inferred, in alignment with Fig. 2(f) trend, the filter enables 20 km transmission below the HD-FEC BER threshold with only linear FFE at the receiver. With PNLE, we could even lower the BER below 1e-3.

3. References

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