Linearization of Directly Modulated Lasers for Enhanced Optical Wireless Communication

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***Abstract*—The demand for high-speed optical wireless communication (OWC) has surged due to the growing number of high bandwidth applications. Directly modulated lasers (DMLs) are a necessary alternative to light-emitting diodes (LEDs) for achieving higher speeds. However, at high data rates, the intrinsic non-linearity of DMLs degrades signal quality, limiting achievable data rates. We demonstrate the application of the ABCD linearization technique to a 2.5 GHz blue laser employing non-return-to-zero (NRZ) and carrierless amplitude/ phase (CAP) modulation. Using a 3.5 GHz PIN photodetector and feed-forward equalizer (FFE), this method improves the achievable data rate by ~1.8 times for NRZ, from 3.8 Gb/s to 7 Gb/s, and by 2.3× for CAP-16, achieving 9 Gb/s. These results validate the ABCD approximation method as a simple yet effective solution for mitigating laser non-linearity and enhancing data rates in high-speed OWC systems.**

***Index Terms*—Optical wireless communications, Laser linearization, Directly modulated lasers**

I. INTRODUCTION

THE rapid growth of high bandwidth applications, such as high-definition video and the Internet of Things has caused severe congestion in the radio frequency spectrum, especially indoors where over 80% of internet traffic originates [1]. Optical wireless communication (OWC) emerges as a promising solution, offering higher data capacity. While light-emitting diodes (LEDs) are widely adopted in OWC due to their simplicity and low cost, their low electrical-to-optical efficiency and limited modulation bandwidth (BW) restrict high-speed performance. In contrast, laser diodes (LDs) offer high modulation BW and optical efficiency, but suffer from non-linearity at high data rates. Equalization techniques, such as machine learning-based equalization, look-up tables and Volterra series equalizers [2, 3] often involve high complexity and extensive computation.

We recently proposed a simpler and computationally-efficient linearization method−the ABCD approximation method [4]–[6] which uses laser rate equations to generate a pre-compensated modulating current. Unlike traditional techniques [2,3], it avoids external hardware, high-order polynomial expansions, matrix operations, and iterative training. Instead, it uses a closed-form expression and basic arithmetic on the desired waveform and its low-order derivatives, as well as knowledge of the laser parameters. The method has proven effective in 850 nm vertical cavity surface-emitting laser (VCSEL)-based short fibre links, improving laser linearity and data rates using non-return-to-zero (NRZ) [5], pulse amplitude modulation (PAM) [6], and carrierless amplitude and phase (CAP) [7]. In visible light communication (VLC), recent works have used blue LDs with avalanche photodiodes (APDs) [8], silicon photomultipliers (SiPMs) [9, 10] and PIN photodiodes [11]–[13] to achieve high data rates. Blue LDs are preferred due to the low attenuation for underwater communications, better matching to the responsivity peak of some photodetectors and possible use as a lighting device with a suitable phosphor. Edge emitting lasers are attractive for their higher optical output, therefore greater achievable link range.

Researchers have also explored various modulation formats, such as quadrature amplitude modulation (QAM) with orthogonal frequency-division multiplexing (OFDM), NRZ with decision feedback equalization (DFE), and discrete multi-tone (DMT) modulation with bit and power loading (BPL), as summarized in Table I [8]–[13]. Despite high data rates, many of these methods require complex experimental setups and advanced signal processing, which limit their practicality.

For the first time, this paper demonstrates the application of the ABCD approximation method to linearize a 405 nm LD in VLC, using NRZ and CAP-16. This method eliminates the need for complex non-linear equalization at the receiver. Unlike QAM and OFDM, CAP modulation [14] utilizes two orthogonal finite impulse response (FIR) digital filters as modulator and demodulator, avoiding local oscillators, RF mixers, phase-locked loops, and the computationally intensive fast Fourier and inverse Fourier transforms required in OFDM [14]. The ABCD approximation method, combined with conventional feed forward equalization (FFE), enhances the data rates, enabling 7 Gb/s (NRZ) and 9 Gb/s (CAP-16) at bit error rate (BER) $< 3.8 \times 10^{-3}$, compared to 3.8 Gb/s (NRZ) and 8 Gb/s (CAP-16) without the method, paving the way for efficient, low-cost, high-speed OWC.

II. METHODOLOGY

A. ABCD Approximation Method

The ABCD approximation [4-6] is a back-calculation technique using electronic pre-compensation to mitigate non-

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TABLE I

LIST OF RECENT EXPERIMENTAL DEMONSTRATIONS OF BLUE LASER-BASED OWC

Year	Laser Model and Type	Laser 3 dB BW [GHz]	λ [nm]	PD Type	Laser Output Power [mW]	PD 3 dB BW [GHz]	Mod. Scheme	Data Rate [Gb/s]	Method	Ref
2020	LP450-SF15, Single Mode	1.2	450	APD	12.8	1	DMT with BPL	6.23	Simplified Volterra post-equalization	[8]
2021	L405P20, Fabry Perot (FP)	2.5	405	SiPM	-	-	NRZ	3.45	DFE and highly sensitive PD	[9]
2022	LP450-SF15, Single Mode	1.2	450	SiPM	9.88	-	NRZ	2	Diversity reception and non-linear DFE	[10]
2023	Osram PL450B, FP	1.8	450	PIN	110	>7	QAM-DMT	19.02	Probabilistic constellation shaping	[11]
2023	Self-design, FP	5.9	451	PIN	-	10	QAM-DMT with BPL	20.06	Self-design laser with low threshold current and high slope efficiency	[12]
2024	Osram PL450B, FP	1.8	450	PIN	20	1.4	QAM with BPL	12.1	Subcarrier intensity modulation with polarisation division multiplexing	[13]
2025	L405P20 FP	2.5	405	PIN	20	3.5	NRZ and CAP-16	7 and 9	ABCD approximation laser linearization	This work

linear modulation dynamics in directly modulated lasers (DMLs) [15]. It employs digital signal processing to generate a pre-compensated modulating current producing a linear optical output. The ABCD approximation simplifies the full back-calculated current, $I_{bc}(t)$ and expresses it in terms of four approximate subcurrents, $\widetilde{I_A}$, $\widetilde{I_B}$, I_C, and I_D [4]:

$$I_{bc}(t) \approx \widetilde{I_{bc}}(t) = \widetilde{I_A}(t) + \widetilde{I_B}(t) + I_C(t) + I_D \qquad (1)$$

$\widetilde{I_{bc}}$ is the ABCD approximated current. I_D is a constant term equal to the threshold current and $I_C(t)$ is a linear subcurrent proportional to the desired photon density, $N_p(t)$ [4]:

$$I_D = \frac{qV}{\tau_e} \cdot \left(N_0 + \frac{1}{\Gamma \cdot g_0 \cdot \tau_p} \right) = I_{th} \qquad (2)$$

$$I_C = \frac{qV}{\Gamma \tau_p} \cdot N_p(t) \cdot \left(1 + \frac{\varepsilon}{g_0 \cdot \tau_e} \right) \qquad (3)$$

where q is the electron charge, V the active region volume, Γ the optical confinement factor, τ_p the photon lifetime, ε the gain compression factor, g_0 the gain slope coefficient and τ_e the carrier lifetime. I_C can be computed via simple arithmetic using laser parameters and $N_p(t)$. The approximate subcurrents $\widetilde{I_A}(t)$ and $\widetilde{I_B}(t)$ are derived from $I_C(t)$ via low-order derivatives and scaling factors [4]:

$$\widetilde{I_B}(t) = b \frac{dI_C(t)}{dt} \qquad (4)$$

$$\widetilde{I_A}(t) = a \frac{d\widetilde{I_B}(t)}{dt} = a \cdot b \frac{d^2 I_C(t)}{dt^2} \qquad (5)$$

Parameter b depends only on the laser parameters, while a depends on both the laser parameters and the operating bias point [4]. $\widetilde{I_B}(t)$ and $\widetilde{I_A}(t)$ are analytical non-linear terms that are responsible for correcting laser non-linearity [4]. They can be computed using simple finite-difference expressions for the first and second derivatives of I_C, along with algebraic scaling. The ABCD approximation method (Eq. 1) requires only two finite-difference operations and four scalar multiplications per sample, making it significantly more computationally efficient than Volterra-based equalizers, look-up tables, and machine learning techniques. These alternatives typically involve hundreds to thousands of multiplications per sample, require substantial memory resources and large matrix operations.

B. Laser Parameters Estimation

A commercially available TO-can packaged 405 nm LD (L405P20, ~ 20 mW) was used in this study. Since the exact device parameters were not available, estimates were extracted from experimental characterization. Particularly, small-signal frequency responses were recorded at various bias currents, along with the laser's threshold current and light-current (L-I) characteristics. The subtraction method [16] was employed to extract the intrinsic parameters of the laser from the measured small-signal (S21) frequency responses. By subtracting the response just above threshold from that at higher bias currents, packaging and mount-induced parasitics are effectively eliminated. The resulting intrinsic responses were then fitted with a three-pole transfer function comprising a second-order intrinsic term, $H_{int}(f)$ and a first-order parasitic term, $H_p(f)$, enabling the laser parameters extraction, as detailed in [5].

These estimated parameters (Table II) were then used in a laser rate equation model to simulate the L-I curve and small-signal frequency responses. Fig. 1 compares the measured and simulated L-I curves, demonstrating good agreement. Fig. 2(a) shows the measured, fitted, and simulated small-signal responses at three different bias currents, while Fig. 2(b) shows the laser's 3 dB bandwidth as a function of bias current, incorporating the effects of laser parasitics [4]. The results indicate a good match between the measured and simulated values, validating the estimated laser parameters.

TABLE II

ESTIMATED LASER PARAMETERS

Parameter	Estimated Value
Carrier Lifetime, τ_e	8.32×10^{-10} s
Photon Lifetime, τ_{ph}	7.43×10^{-12} s
Optical Confinement Factor, Γ	3.56×10^{-2}
Gain Slope Coefficient, g_0	6.50×10^{-7} m^2
Spontaneous Emission Factor, β	1.55×10^{-3}
Gain Compression Factor, ε	6.88×10^{-23} m^3
Carrier Density at Transparency, N_0	7.99×10^{18} m^{-3}
Volume of the Active Region, V_a	1.17×10^{-11}m^3

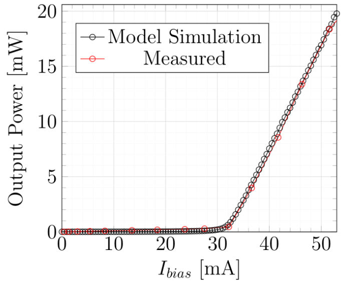

Fig. 1. Measured vs simulated LI curve of the L405P20 laser.

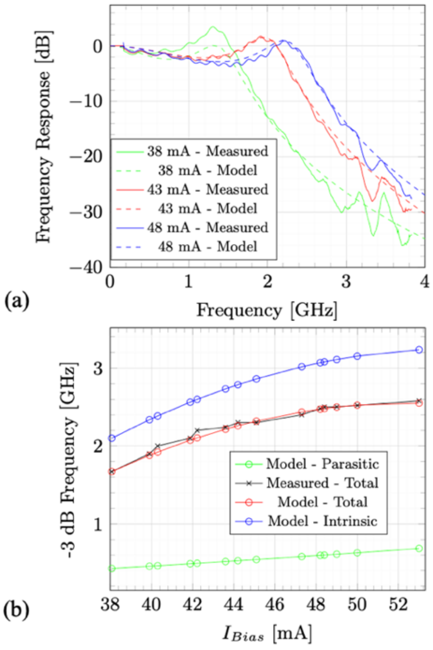

Fig. 2. (a) Measured (solid lines) vs simulated (dashed lines) frequency response curves at three bias currents (b) Measured (cross) and simulated (circle) -3 dB bandwidth.

C. Experiment Setup

The experimental setup is shown in Fig. 3. The laser is biased at 50 mA, modulated with a pseudorandom binary sequence (PRBS-11) signal. The modulating current is calculated offline and loaded onto an arbitrary waveform generator (AWG, Tektronix 70001A, 14 GHz bandwidth, 50 GS/s). This AWG signal is then amplified by a 40 GHz RF amplifier, producing a peak-to-peak modulating voltage (V_{PP}) of ~0.4 V. This amplified signal is combined with the DC bias current using a high bandwidth bias-T, and fed into the LD. An aspheric condenser lens is placed in front of the laser to collimate the light. The receiver is an Alphalas PIN PD (UPD-50-SP) with a measured BW of 3.5 GHz. The 405nm LD is not eye-safe due to its high optical power (~20 mW). Therefore, the transmission experiment is performed at 15 cm distance by enclosing the setup in a box to ensure laser safety compliance. The short distance still provides a valid proof-of-concept for demonstrating the effectiveness of the ABCD approximation method in OWC.

At the receiver, the light beam is focused on the PIN PD using another condenser lens. The optical signal detected by the PD is converted into an electrical signal and amplified using a 6 GHz amplifier, which is then recorded using an oscilloscope (Tektronix DPO77002SX). The captured signal is post-processed in MATLAB. A feed-forward equalizer (FFE) is applied at the receiver to mitigate linear distortions. The receive FFE length is kept the same for both the conventional and the ABCD approximation cases to ensure a fair comparison of the system performance. Finally, the BER is calculated to evaluate the system performance.

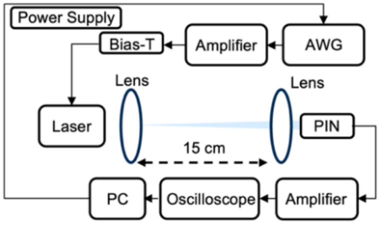

Fig. 3. Experiment setup.

III. EXPERIMENT RESULTS

The BER performance of the system with and without the ABCD approximation method for various data rates when using NRZ is shown in Fig. 4. The red line shows the ABCD approximation method with receive FFE, while the green line shows the results when only the receive FFE is applied. The dashed black line shows the FEC limit of 3.8×10^{-3}. The maximum data rate achieved without the ABCD approximation method is 3.8 Gb/s. In contrast, the ABCD approximation method reduces the laser non-linearity and increases the achievable data rate to 7 Gb/s, corresponding to a ~1.8x data rate improvement. The subplot in Fig. 4 shows the eye diagrams at 7 Gb/s after a 9-tap receive FFE for conventional NRZ modulation and the ABCD approximation method. Receive FFE-only NRZ results in a completely closed eye, due to severe laser non-linearity. In contrast, the ABCD method achieves a well-opened eye. These results validate the effectiveness of the ABCD approximation method in reducing laser non-linearity and extending data rates in OWC links.

The data rate is extended to 9 Gb/s using 2.25 Gbd CAP-16 (Fig. 5). Without the ABCD approximation, conventional CAP-16 exhibits significant non-linearity, even with a 42-tap receive FFE using the recursive least squares (RLS) algorithm (Fig. 5(a)). This non-linearity disrupts signal orthogonality, resulting in a high EVM of 23.53% and a BER of 2.7×10^{-2}, exceeding the FEC threshold. Consequently, the symbol rate must be reduced to 2 Gbd to meet FEC threshold, limiting the achievable data rate to 8 Gb/s. In contrast, the ABCD approximation enables 2.25 Gbd (9 Gb/s) with a BER of 3.6×10^{-3} and an EVM of 17.04% (Fig. 5(b)). The lower data rate improvement obtained in CAP-16 compared to NRZ is due to the lower symbol rate, leading to lower laser non-linearity−consistent with prior observation in [7]. Nevertheless, the data rate has been extended by 2.3× when applying CAP-16 and ABCD approximation, compared to NRZ with only FFE. However, achieving these results requires relatively high optical power due to the low responsivity of silicon-based PIN PDs in the blue-light region. The relatively high FFE tap count reflects system constraints: limited receiver bandwidth (3.5 GHz) and poor PIN responsivity for wavelengths shorter than 400 nm (<0.1 A/W) [17], degrading the SNR. Despite these constraints, the ABCD approximation method improves signal linearity and reduces equalizer burden. Under identical 42-tap FFE conditions, it reduces the noise enhancement factor (NEF) [18] significantly, from 1.8 dB (without ABCD approximation) to just 0.163 dB, demonstrating its advantage in producing a more linear optical waveform. Future work will explore alternative PDs (e.g SiPMs) to overcome responsivity limits and assess the achievable data rate and transmission range.

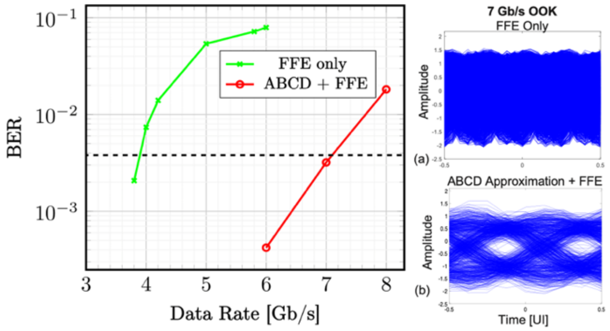

Fig. 4. BER comparison at various data rate with NRZ. Insets are the eye diagrams at 7 Gb/s using (a) 9-taps FFE only (b) ABCD approximation and 9-taps FFE.

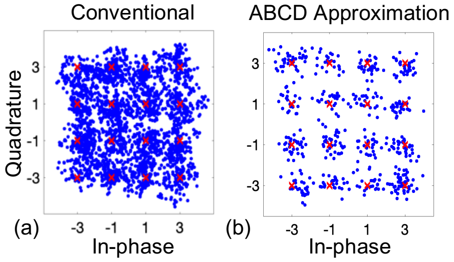

Fig. 5. 2.25 Gbd (9 Gb/s) CAP-16 constellation diagram after 42-tap FFE (a) conventional (b) ABCD approximation.

IV. CONCLUSION

We demonstrate the application of the ABCD approximation method in OWC to achieve higher data rates by reducing laser non-linearity under direct modulation, using NRZ and CAP-16 modulation. In a 15 cm OWC link with a 2.5 GHz, 405 nm laser and a 3.5 GHz PIN PD, the method enables transmission at 7 Gb/s with NRZ and 9 Gb/s with CAP-16. This corresponds to data rate improvements of 1.8× and 2.3×, respectively compared to NRZ with only FFE. These results highlight the ABCD approximation as a simple yet effective technique for improving laser linearity and advancing high-speed OWC.

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