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# Direct and External Hybrid Modulation Approaches for Access Networks

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## Abstract

The demand for low-cost high-speed transmission is a major challenge for 5G future networks. To meet this optical communication demand, holistic and painstaking approaches are required in designing a simplified system model. Since the demands for high bandwidth are growing at unprecedented speed as we approach the Zettabyte era, it is crucial to minimize chromatic dispersion (CD) associated to high bit-rate signals. Mitigating CD electronically comes at high cost which may not be compatible with 5G. Photonic Integrated Circuit (PIC) as an enabler for fast speed optical transmission is still undergoing its growth stage and its major speed and efficiency have not yet been attained. However, proper and right combination of components and approaches can potentiate this technology in a more cost-efficient way. Hybrid modulation (HM)-PIC presents a simplified approach in terms of cost and efficiency for 5G networks. Hybridization of existing modulation components and approaches in PIC can enhance the generation of high bit-rate signals without the need for electrical CD compensation. A detailed study of hybrid multilevel signal modulation concept as a valuable solution for Data Centers (DC) high data-rate signals and next-generation Passive Optical Networks (PONs) is proposed.

**Keywords:** photonic integrated circuits (PIC), hybrid modulation (HM), direct modulation laser (DML), external modulation laser (EML), simplified high bit-rate signal generation, chromatic dispersion (CD), insertion loss (IL), chirp managed lasers (CML), optical spectrum reshaper (OSR)

## 1. Introduction

In the era of explosive demand for bandwidth and complex broadband transmission attributed to the fifth-generation (5G) and beyond, strategic positioning of fiber optics communications is imperative considering its huge advantages in terms of high-speed transmission, simplified design and low cost implementation [1].

Fiber Optics communication, which is carried out through photon, has been a promising approach that can conveniently guarantee the requirements of high data transmission. However, the existing technologies will require complete

overhauling, upgrading, or redesigning for effective results [2]. Unarguably the 5th and 6th generations of wireless networks cannot sufficiently guarantee their expected output in terms of speed, latency and spectral efficiency without improved channel architectures.

Therefore, there is an urgent need to further optimize optical properties to meet the current and future demands for high-speed data communications [3]. Fiber optics on its own with peak-to-peak throughput of 100 Gb/s is unique among other communication channels, and as of today, its capacity in terms of speed and convenience of communication has not been fully utilized [1].

Similarly, PIC as an enabler for optical communications presents a promising approach for conveniences of communications in terms of low footprint, low cost implementation, and very high speed [2, 4]. Therefore, increasing data rate and mobility in the evolving technologies require an increase of data traveling in the networks, introducing new requirements (e.g., speed and latency) for the components, e.g., PIC building blocks (BB). Although, PIC components under terahertz speed is a promising technique to guarantee the requirements of future networks, the maturation of the integrated photonics is still ongoing.

Furthermore, to strengthen the position of fiber optical communications for the emergence of hyperscale future transmission such as hyperscale data centers (HDCs) and to continually improve the amount of data transmission over optical networks through modulation and multiplexing approaches, this chapter will address a detailed description of DML and EML modulation schemes, and improved hybrid approaches, a valuable solution to attain the overcoming requirements of high-speed signal transmissions.

Conventional approaches are carried out through direct modulation laser (DML) and external modulation laser (EML) respectively which cannot guarantee the demands of future networks due to their respective limitations [2, 5, 6]. Although DML is simple in design and can generate high power budget when properly optimized but, the signal is degraded due to high CD, induced adiabatic chirp, phase noise, and low extinction ratio (ER). Consequently, these limit DML transmissions to a short distance of about 10 km and its inability to cope with high bit-rate transmissions [5–7].

EML on the order hand outperforms DML with reduced chirp and better reach. Nevertheless, the signal is also limited due to size, low optical power and high driving voltage among others [2, 8, 9]. Hence, a hybrid combination and optimization of these modulation processes can be seen as a powerful approach.

With the HM method, high bit-rate signals can be generated in a simplified way with a low footprint, low energy consumption and less complexity in meeting the demand for future networks [2].

This chapter provides a detailed study of the development and optimization of a simplified optical transceiver for high data rate 5G optical transmission, in order to manage future competitive markets necessities in its migration to 100G and 400G Ethernet, by replacing the single-mode 10G-SFP+ used for 4G networks. Moreover, the access and aggregation layers patterned with Dense Wavelength Division Multiplexing (DWDM) transceivers having bit-rate as high as 400G designed for metro access, metro convergence and core layer access networks, are also studied.

With HM approach, simplified and high bit-rate intensity modulated signals can be generated without electrical pulse shaping, digital to analog conversion (DAC), and digital signal processing (DSP) compensation [2].

The remaining part of this chapter is arranged as follows: in section 2, details signal modulation approach for PIC is discussed follow by section 3 where we presented the novel HM approach and the results of our simulations. We draw the conclusion in section 4.

## 2. Signal modulation in PIC

The crucial function of modulators in optical communications is the conversion of the electrical information input signal into its corresponding optical domain which is placed on the optical signal as a carrier before being launched into an optical communications channel. This process is carried out in the optical transmitter, where an optical signal from an optical source such as a semiconductor laser or light-emitting diode (LED) is either directly or externally modulated. Optical signal has three major properties which are amplitude, frequency and phase. However, the message electrical signal is biased to manipulate any of these optical properties so that information can be sent along optical channels [2, 9].

Modulation of the optical carrier properties mentioned above could be done directly or externally [5]. Direct modulation is achieved using a DML [8], while the external modulation, which is equally referred to as external modulation laser (EML), can be either through electro-refractive using Mach Zehnder Interferometer (MZI) [9] or electro-absorption using an electro-absorption modulator (EAM) [7, 9].

The simplicity of design and cost [9, 10] make DML a preferred choice, nonetheless several constraints make it undesirable for high bitrate and long-distance transmission [7]. These constraints include low bandwidth, low efficiency, CD caused by induced chirp which imposes signal phase noise, refractive index change of the active layer by carrier density modulation and relatively low ER [5, 6]. DML induced chirp can be transient or adiabatic. Chirp due to transient gives a nonlinear gain which occurs during the bit transitions, while the adiabatic chirp is the spontaneous emission that occurs in the laser, which is responsible for the blue-shifting of bit 1 relative to bit 0 [11]. As a result, the increase of bit-rate in DML causes the signal to suffer a very pronounced pulse broadening due to CD [6], mainly when the bit-rate is increased beyond 10 Gb/s [12]. The chirp in DML is mainly influenced by the linewidth enhancement factor, which is also known as Henry factor limiting within 2 and 8 for DFB laser, and consequently, the signal of 10 Gb/s transmission could not go beyond 10 km [13].

On the other hand, external modulation approaches can achieve high ER, high data-rate, and lower modulation distortion. Unfortunately, this comes with additional system complexity and cost compared to direct modulation [14]. For the external modulation, EAM offers lower cost and size combining with a considerably higher speed when compared to MZI [9, 15]. EAM can achieve better speed with low CD as a result of its zero or negative chirp [6] with the inherent advantage of low driving voltage and the possibility of monolithic integration with a DFB laser on a single waveguide, which reduces channel insertion loss (IL) [9, 16, 17]. Furthermore, EAM optical modulation does not affect the laser properties unlike DML [7] and its low CD can achieve improved speed (25–40 Gb/s) and longer distance (10–40 km) [7, 9]. Additional details regarding the two technologies are provided in the subsections 2.1 and 2.2. Presented results were attained by VPIphotonics® transmission simulations.

### 2.1 DML signal generation

In this approach, an electrical signal is directly injected into the lasing cavity in an attempt to manipulate the stimulated emission present in the laser cavity. By this, a high-frequency electromagnetic signal with information could be sent via optical channel after modulation [9, 14]. **Figure 1** gives an illustration of how the DML approach can be achieved and its chirp effects.

Practically, semiconductor lasers such as distributed feedback laser (DFB), constricted-mesa lasers and Fabry-Perot (FP) lasers are the major lasers used for
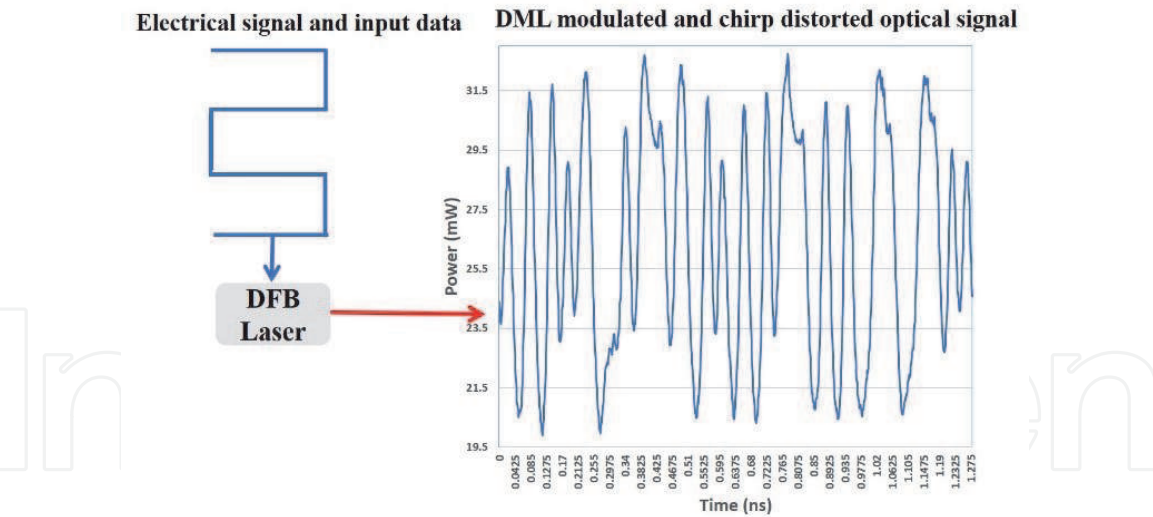
**Electrical signal and input data**   **DML modulated and chirp distorted optical signal**



**Figure 1.**
*DML showing electrical signals without chirp before modulation and optical signal after modulation with chirping effect.*

DML purposes. It is important to note that DML is simple and cost efficient but can only be applied with low bit-rate and short-reach as a result of chirp due to spectral broadening associated with the biasing current during modulation. This is due to accompanying phase modulation (PM) to the desired intensity modulation (IM) during this process [18]. The level of the chirping imposed on the modulated pulse largely depends on the driving condition ($I_{bias}$ and modulation current ($\Delta I$)) and the laser type.

### 2.1.1 DML chirping effects

The chirp associated with DML can be subdivided into transient and adiabatic chirp as depicted in **Figure 2**. The presence of chirp in the modulated pulse leads to high CD and invariably inter-symbol-interference (ISI) which adversely weakens the reach and effects of DML transmission.

According to [19], transient chirp is associated with the relatively small frequency difference between the steady-state of signal pulse levels of ones and zeros. This frequency difference leads to ringing and significantly obvious overshooting of optical output power and frequency deviations.
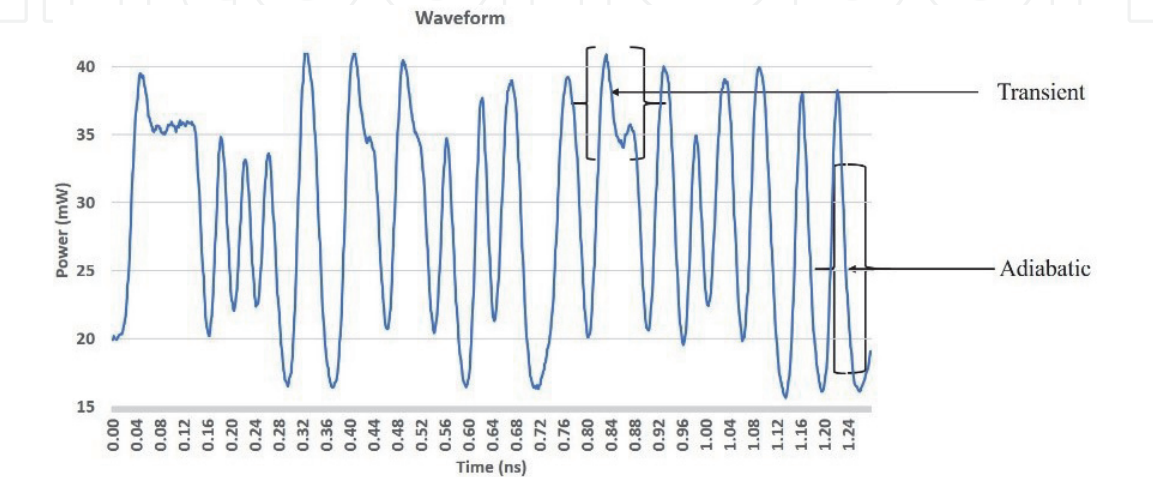


**Figure 2.**
*DML power time domain response showing transient and adiabatic chirp.*

Adiabatic chirp at the same time can be described with the damping oscillations and large frequency differences between pulse ones and zeros.

Compensating the chirp and CD in DML comes with its own cost and complexity. Some of these approaches are the use of dispersion compensation fiber (DCF), electrical signal compensations through decision feedback equalizer (DFE), feed-forward equalizer (FFE), continuous-time linear equalizer (CTLE), digital signal processing (DSP), electrical pulse shaping and finally, optical CD compensation through optical spectrum reshape (OSR) [20]. This OSR method is better detailed in the subsection 3.3.

Nevertheless, progressive works to reduce the effect of chirp on DML show improved results. For instance, in [21], an InGaA1As/InGaA1As multi-quantum well (MQW)-DML was grown on an n-doped InP substrate by shortening the laser cavity length to less than 150 μm via positioning of a passive waveguide in the front of the DFB laser. The DML was operated at 45 mA driving current with 43 Gb/s bit-rate, the optical signal obtained after 40 km presents a clear eye signal at 25 °C which shows an improved bit-rate possibility higher than 10 Gb/s over DML.

Similarly, the research work in [22] also presents a 40 Gb/s DML optical signal that used passive feedback laser (PFL) realized around 1300 nm and 1550 nm wavelength region. In this work, DFB and integrated passive feedback section (IPF) were combined enabling the suppression and control of the phase feedback field with the modulation performance of the stationary operating laser.

Other works in [23–25] also present similar improvements in the design of DML with higher bit-rate and improved fast speed transmission. The authors in [23] used InP-on-Si to achieve 45 Gb/s and 25 GHz 3-dB modulation bandwidth at a relaxation oscillation frequency of 10 GHz using NRZ encoder. The fabricated laser has two sections of around 250 μm each with an active region on InGaAsP separate confinement hetero-structure (SCH). A clear eye diagram after a 2 km transmission of 45 Gb/s was obtained with BER lower than 7% Hard Decision (HD) forward error correction (FEC) and received optical power (ROP) around −7 dBm.

### 2.1.2 DML signal optimization

To further investigate the behavior of DML, we carried out a simulation study of a rate equation model of a semiconductor DFB laser. In order to reduce the effect of the unwanted transient chirp on the modulated signal, it is highly advised to bias the laser far away from the current threshold [9, 26], allowing to obtain high optical output power after modulation. Although, this is a trade-off with the optical signal ER. In our case, the laser current threshold is obtained around 10 mA and as we biased away from this point, the output optical signal increases with reduced transient chirp while the signal ER reduces.

The block diagram for an intensity DML is presented in **Figure 3** and the DML parameters used are summarized in **Table 1**.
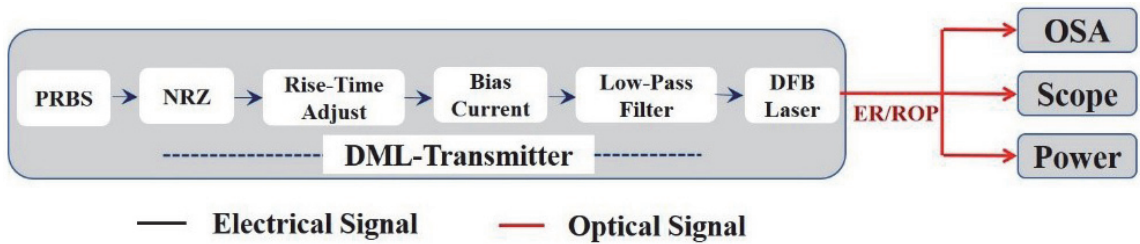


**Figure 3.**
*Block diagram of a DML characterization bench.*

| Simulation Parameters | Value |
|---|---|
| BitRate | 10 Gb/s |
| Wavelength | 1.57 μm |
| Laser Bias Current | 90 mA |
| Laser Confinement Factor | 0.5 |
| Henry Linewidth Enhancement Factor | 3.0 |

**Table 1.**
*DML simulation parameters.*

A non-return to zero (NRZ) electrical modulation scheme is supplied with pseu-dorandom binary sequence through modified Wichman-Hill generator with length M bits = TimeWindow*Bit-Rate, which is applied on the DFB laser while biasing at given current in order to modulate its amplitude [27]. The transmitted optical pulse after modulation for the giving rate equation laser is expressed by Eq. (1).

$$A(t)_{DML} = I_{bias} + \sum_{k=-\infty}^{\infty} A_D I_{pulse}(t - kT) \tag{1}$$

Where $A(t)_{DML}$ is the modulated optical pulse from the DML transmitter, $I_{bias}$ is the bias current, $A_D$ is the PRBS data sequence of the form zeros and ones, each indexing with k, $I_{pulse}$ is the encoding signaling format used (return to zero (RZ), NRZ, etc.), and T the bit period.

The received optical power (ROP) and ER at different laser modulation current and bias are depicted in **Figure 4**. In section 3, this obtained result will be optimized through our simplified HM approach.
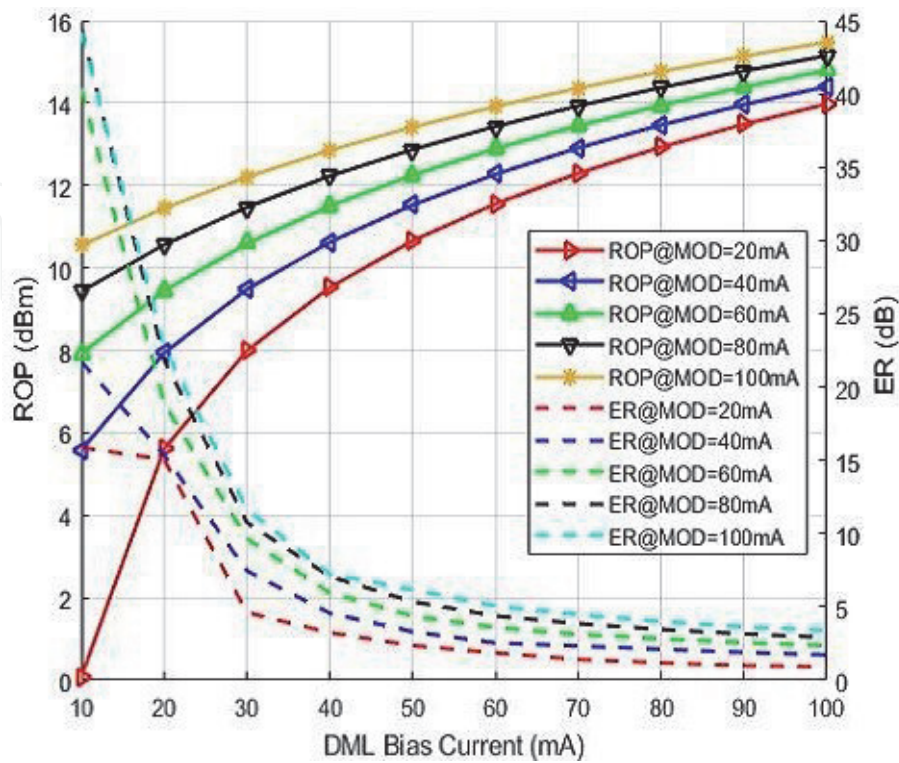


**Figure 4.**
*ER and ROP variation against DML biasing current.*

## 2.2 EML signal generation

EML signal generation as an alternative to DML can eliminate significantly the frequency chirp effect associated with direct modulation scheme [9]. The procedure requires a continuous wave laser (CW-laser) providing constant optical signal into the external modulator and an external electrical signal is applied to manipulate any of the desired properties (intensity, phase and frequency) of the light. A standard EML operation mode is depicted in **Figure 5**, comprising the CW laser, external modulator and the external electrical driving voltage.

As mentioned in the introduction section, two main approaches of external optical modulation are: i) the electro-refractive (LiNBO3 MZM); and ii) the electro-absorption (EAM) [13]. We shall briefly discuss design approaches and the mode of operations of these devices.

### 2.2.1 MZM

The overall behavior of the MZM as presented in **Figure 6** largely depends on its design and configuration, e.g., based on the lithium niobate crystal. A good design MZM has high ER with low chirp, which requires high driving voltage. The amount
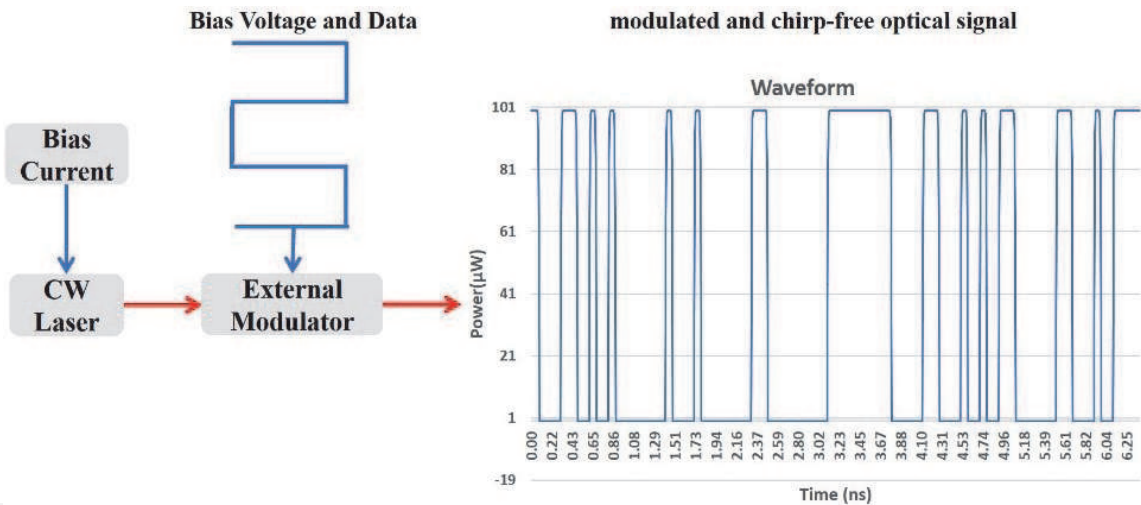


**Figure 5.**
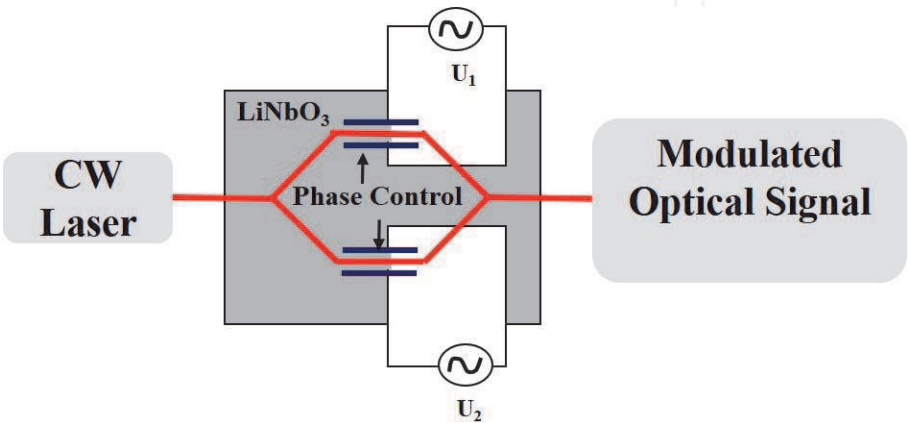*Block diagram of an external modulation laser.*



**Figure 6.**
*Typical mode of operation of a MZM modulation scheme.*

of driving voltage will then result in a large dependence of device's efficiency [22]. This voltage effect can be translated by MZM power transfer function in Eq. (2).

$$P_0(t) = \alpha_M P_i \cos\left\{\frac{\pi V(t)}{2V_\pi}\right\} \tag{2}$$

Where $P_0(t)$ is the transmitted optical power from the output of the interferometer, $\alpha_M$ is the modulator total IL, $P_i$ is the input optical power from the CW laser to the modulator, $V(t)$ is the time-dependent externally applied electric voltage, and $V_\pi$ the driving voltage to exert a $\pi$ phase shift on the light wave carrier along the optical path of the modulator. The major drawback comparing with EAM modulation schemes is its bigger size and high driving voltage requirements, which makes it more expensive to design and with larger footprint in the integrated circuit [9].

### 2.2.2 EAM

EAM is considered an attractive modulation approach for fast-speed optical communications due to its low driving voltage, high bandwidth, high modulation efficiency and the possibility of monolithic integration with other semiconductor devices [28, 29]. EAM is an intensity modulator that changes the absorption properties of the carrier optical signal through the application of voltage V(t) around the band edge of the waveguides [9, 30].

Unlike MZM that modulates both intensity and phase of the carrier signal, EAM as an intensity modulator shows additional advantages, e.g., its linearity in the amplitude multilevel modulation, which offers lower total harmonic distortion when comparing to the MZM [9]. Nevertheless, MZM can achieve higher ER, an EAM with similar ER would imply increase size and therefore increase IL [9, 14].

The driving of EAM is attained with negative bias voltage to guarantee an efficient light absorption of the modulator [9]. To work in the linear region of the EAM we choose the driving voltage range [-4 V to −1.5 V], see **Figure 7**.
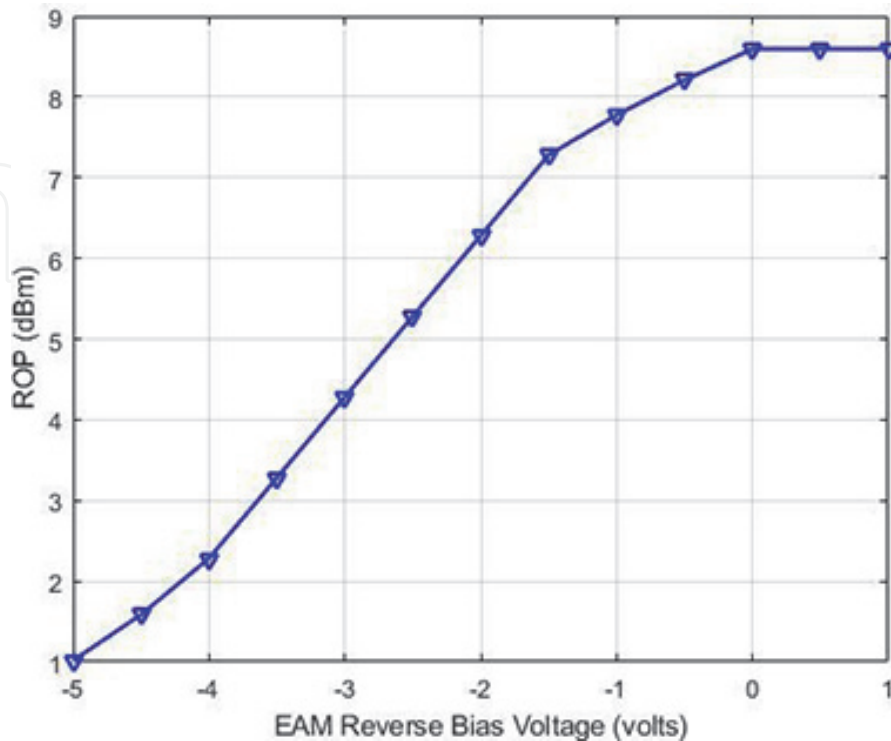


**Figure 7.**
*EAM ROP vs. V curve. Linear region can be spotted between −4 V and − 1.5 V (laser power = 10 dBm).*

Biasing the modulator must be kept within the linear region to prevent signal distortion [30]. However, voltage biasing here presents a trade-off between modulation efficiency (eye-opening) and the EAM linearity limit. With higher amplitude, EAM linear region can be extended but this will sacrifice signal efficiency with the distorted eye. In our case for 50 μm long EAM, the bias voltage is fixed at −3 V with a linear region between −4 V and − 1.5 V and the voltage swing of 1.5 V.

In the design of EAM, two major approaches are employed: i) a bulk process through Franz-Keldysh Effect, and ii) a Multi-Quantum Well (MQW) through Quantum Confined Stack Effect (QCSE) [9, 31]. Investigations show that MQW-EAM is preferred over Bulk-EAM due to its large absorption coefficient [16, 28, 31–34], leading to higher ER [35].

Considering EAM parameters from published studies [2, 32, 35–38], we simulated the modulation amplitude transfer function T(t). EAM inherent properties used as a figure of merit for a wavelength of 1.57 μm and EAM of 200 μm in length, were 0.055 dB of IL and 0.115 dB of ER per 1 μm length of EAM. Therefore, an increase of EAM ER (and thus EAM length) is given at the expense of an IL increase. This is a major setback for the use of EAM in EML modulation schemes.

Furthermore, we simulated T(t) parameters interpolation to mimic the behavior of 200 μm EAM and obtained T(t) against V(t) for different EAM length at 1.57 μm optical wavelength based on the properties of EAM length stated above.

The obtained results of EAM length versus its IL and ER are provided in
**Figure 8**.

The compromise between EAM IL and ER, by changing EAM size, allow us to reach the necessary requirements of our optical transmitter, essential information to model our hybrid transmitter as presented in the section 3.

Operation of EML through the EAM intensity modulator stated here can be expressed by Eq. (3).
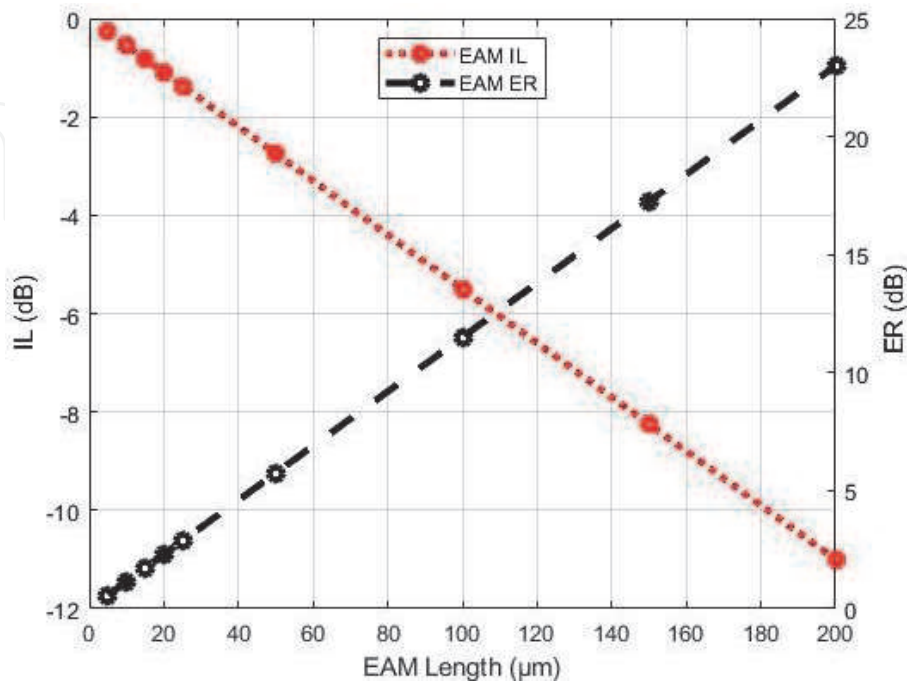
$$A(t)_{EML} = T(t).A(t)_{cw} \tag{3}$$



**Figure 8.**
*EAM ER and IL versus EAM lengths. For the ER values, the EAM was biased at −4 V and modulated at 0 V.*

Where $A(t)_{EML}$ is the modulated optical signal output from EAM, T(t), the complex field-intensity transmission function which depends on the length of EAM and the bias voltage while $A(t)_{cw}$ is the constant optical carrier signal supplied by the CW laser. T(t) can be specified in dB by squaring its magnitude giving by

$$T(t)_{dB} = 10 \cdot \log\left( |T(t)|^2 \right) \qquad (4)$$

The modulating voltage v(t) and the bias voltage $V_o$ which are used for electrical driving of the modulator are related to T(t) according to Eqs. (5) and (6).

$$V(t) = V_o + v(t) \qquad (5)$$

$$T(t) = T(t)_{dB} \cdot V(t) \qquad (6)$$

## 3. Hybrid modulation (HM)

An obvious treat on conventional communication procedures with the current BB which leads to high system impairment and overloads has led scientific community to think further on the prospect of hybrid combination of processes and components [39]. This approach can be implemented monolithically in an InP-based platform, allowing higher spectral efficiency and the ability to generate high bit-rate signals [40].

Different limitation can be addressed for DML and EML modulation schemes. For instance, DML can only be used for relatively lower speed ≤25 Gb/s and cannot be transmitted beyond 10 km for data-center interconnect (DCI) and passive optical networks (PON) systems [7]. On the other hand, external modulation through EAM is limited by high IL values to address requirements of high ER [2]. Combining the advantages versus limitations of these two modulation schemes can result in improvements of the overall signal generation for DCI and PON systems, by mitigating the problems of transmission loss and group velocity dispersion (GVD).

Past works on optimization of transmission efficiency are associated with costly and complex system designs [22–25]. Hence, a procedure to reduce or eliminate these limiting factors are vital to the success of 5G deployment. Since PIC is still undergoing its maturity stage, its best design, functionality and efficiency are still under research. Several approaches used for impairment compensation can be optimized through hybrid combinations of BBs. In this work, we have conducted extensive studies and simulations of procedures for signal generations through direct and external modulation schemes. DML limitations have been discussed in section 2.1. External modulation on the other hand presents an attractive alternative to DML although, nevertheless with the constrain of high IL, which requires a laser with enough output power to overcome this loss.

Thus, HM concept appears as a useful approach, by exploring the advantages of both direct and external modulation approaches and components functionalities to produce a full integrated system. One major obstacle in the proposed hybrid combination is the presence of short noise dominated by photons from the DML due to spontaneous emission and the electron–hole recombination which significantly reduces the signal-to-noise ratio (SNR) of the hybrid transmitter [9]. We have provided a measure to reduce this noise and also reduce the transient chirp in the DML pulse through optical signal reshaper (OSR) approach which will be presented later in this section.

### 3.1 HM-model

Modulated optical signal from DML is launched into the optical signal input of the characterized EAM under study in order to re-modulate the optical signal for intensity signal generation. The T(t) earlier described in Eq. (6) that depends on the driving bias voltage and length of the modulator is loaded as a data file through VPIphotonics transmission maker optical simulator to control the EAM [41]. Therefore, for HM-model, Eq. (3) can be rewritten as presented in Eq. (7)

$$A(t)_{HM} = T(t) \cdot A(t)_{DML} \tag{7}$$

From the Eq. (3) We have replaced the $A(t)_{cw}$ with $A(t)_{DML}$ obtained from Eq. (1) which is the modulated optical signal launched from the DML and $A(t)_{HM}$ is the output of the hybrid transmitter.

$T(t)$ enables us to control and decide on the length of the modulator that is sufficient to guarantee the desire ER and with the biasing of the DML current, we can adjust the power budget to compensate the IL imposed by EAM as a result of modulator length.

The corresponding schematic is presented in **Figure 9**. It consists of PRBS and NRZ electrical signal encoder used for driving DML. In the case of HM, the electrical signal is split into two to drive both DML and EAM. the EAM amplitude is configured with reverse bias voltage of −3 V which fall within the EAM linear region.

The obtained signal $A(t)_{EAM}$ can be optimized with high ER and power budget sufficient for DCI and PON. The optimization of our hybrid modulator was done with optical wavelength at 1.57 μm where we obtained the parameters for EAM characterization.

The measured ER and ROP by changing the length of EAM and modulation current at fixed bias (90 mA) current of DML are presented in **Figure 10** and **Figure 11** respectively. The DML ROP and ER before launching the optical signal for intensity modulation are also highlighted on the graphs.

We further launched the optical signal at different EAM lengths tested into optical distribution networks (ODN) ranging from 5–40 km in order to study the behavior of the signals and responses to dispersion and non-linearity in the fiber, see **Figure 12**. With increased EAM length, the signals present an improved error rate from the 5 km starting point up to 20 km which is attributed to high ER.
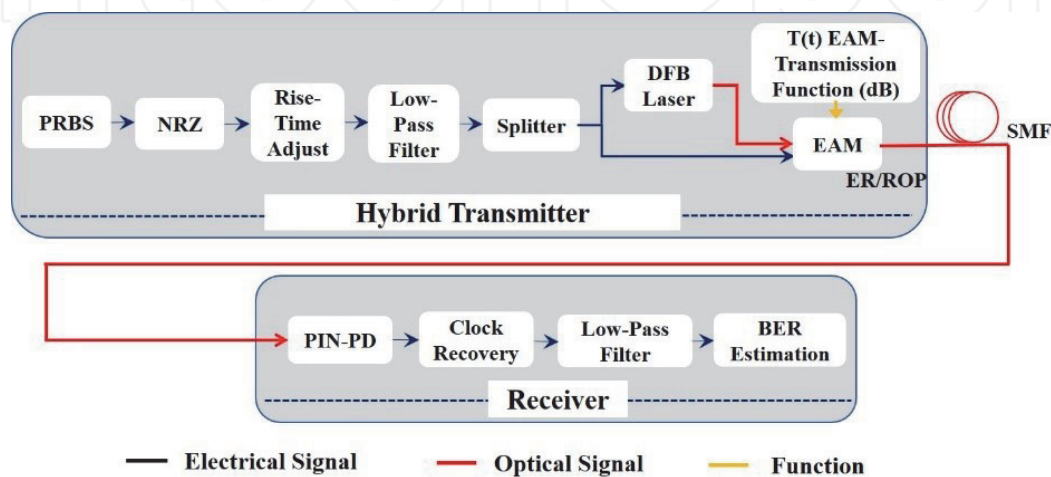
**Figure 9.**
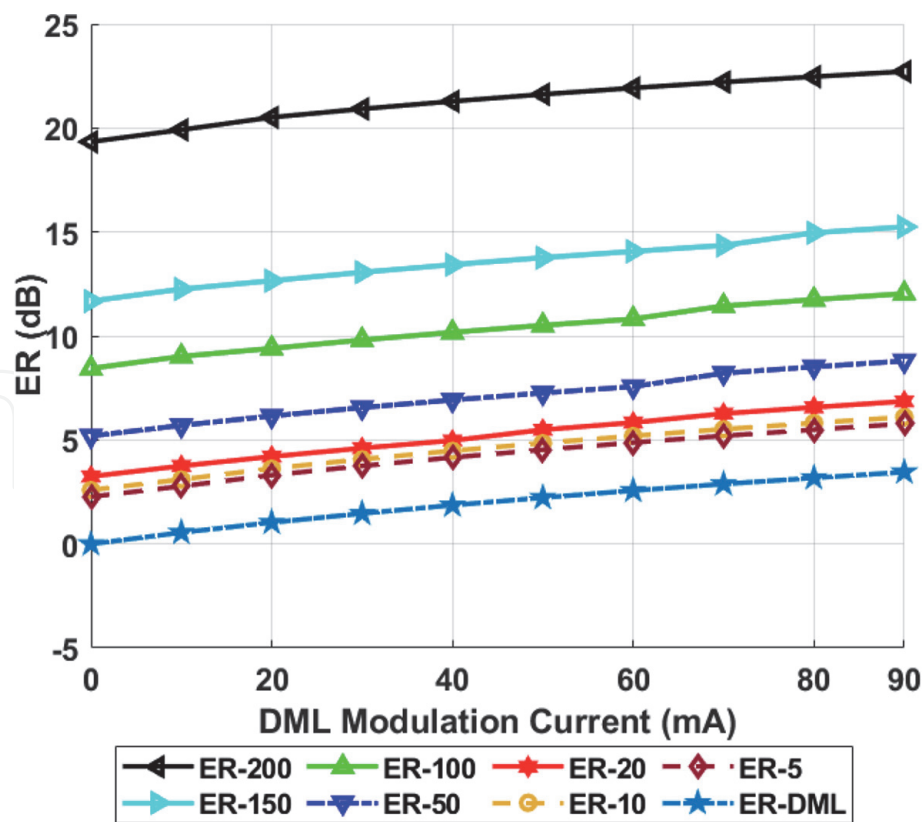*Simulation setup for HM approach.*

**Figure 10.**
*ER at hybrid transmitter's output for different EAM-length against DML modulation current: EAM bias, $V_o$ = -3 V, EAM voltage swing, $v(t)$ = 2 V, DML Bias = 90 mA.*
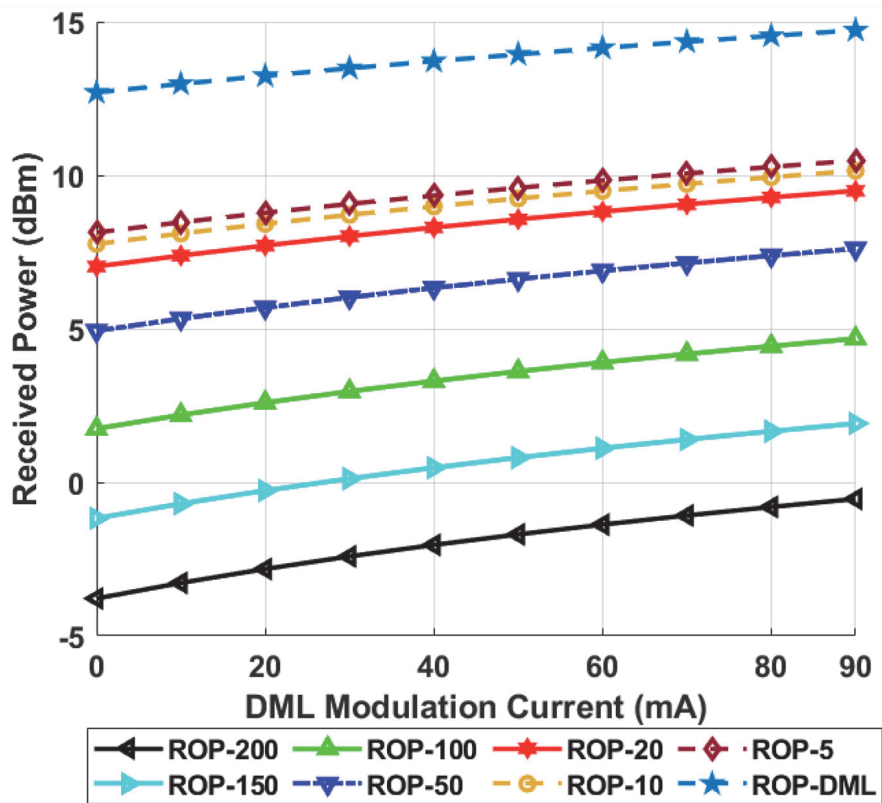


**Figure 11.**
*ROP at hybrid transmitter's output for different EAM-length against DML modulation current: EAM bias, $V_o$ = -3 V, EAM voltage swing, $v(t)$ = 2 V, DML Bias = 90 mA.*
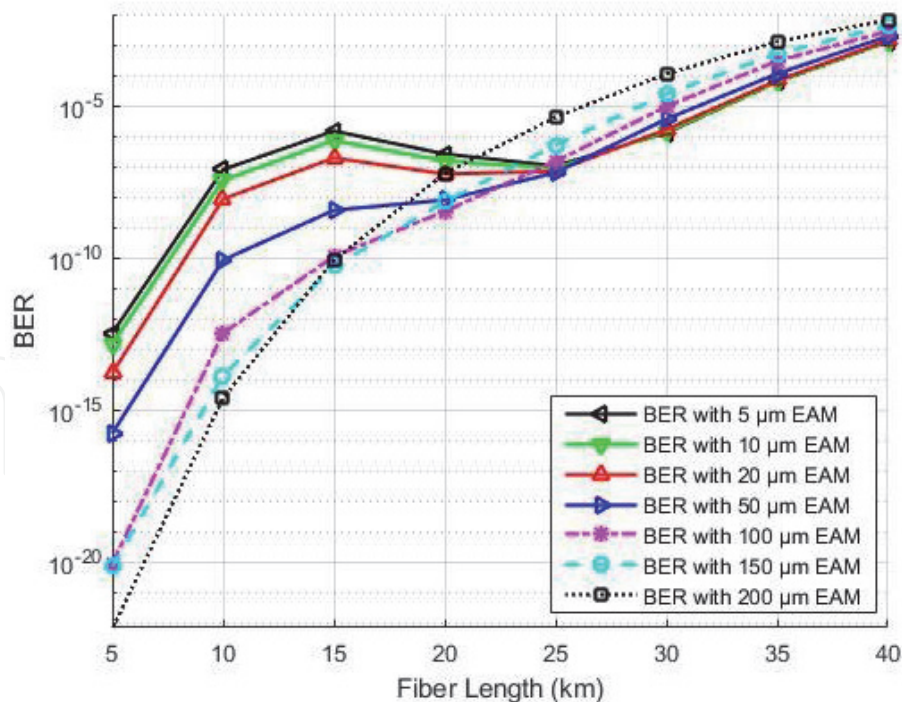
**Figure 12.**
*BER and ROP versus fiber length for optical signals stemming from EAM with different lengths.*

However, since higher ER also contributes to higher IL coupled with the attenuation in the fiber, the signal with lower EAM length (EAM = 5 μm) gives a better error rate than when EAM length is 200 μm as we continue to increase the length of the fiber as presented in **Figure 12**. At 40 km all the signals from different EAM lengths tested were received at an error rate less than $10^{-3}$.

### 3.2 Simplified high bit-rate multilevel signal generation

Short reach fiber optic communication such as PON, short-reach video on demand (VoD) and DCI have recently advanced the demand for bandwidth [42]. This demands more efficient and advanced high spectral modulation format to replace the conventional NRZ line code [43] in order to guarantee high data rate beyond 50 Gb/s per channel [41, 44]. IEEE 802.3 group quad small form-factor pluggable (QSFP) 400 Gb/s specifications for short-reach data center communication systems have been studied progressively. Better data rate usage such as 56 Gb/s per channel can help to reduce system design complexity and cost [44–46]. Studies show that access, aggregation and core networks bandwidth demand in 5G can be adequately guaranteed with 400 Gb/s PAM-4 signal generations with either 56 Gb/s 8-channel or 100 Gb/s 4-channel networks [47, 48]. With this provision, some key requirements of 5G networks such as low cost, high performance and high bandwidth can be adequately guaranteed.

PAM-4 is a multi-order modulation approach which presents a bit-rate twice of the NRZ signal line code under the same baud-rate using four levels for signal transmission with two bits of logical information per each clock period [48]. However, PAM-4 presents a high degree of complexity in the signal generation, coupled with its sensitivity to amplitude noise which leads to a high signal to noise ratio (SNR) [45]. This is because PAM-4 signal have four levels with three eyes, which implies that, its signal is generated with an amplitude (A) of A/3 compared to NRZ that has a SNR = A. With this deficiency, PAM-4 signal is at least three times more sensitive to amplitude noise than NRZ.

To generate a PAM-4 signal for optical communication however, some complex system designs are used. In [48], physical coding sub-layer (PCS) is used to support forward error correction (FEC) at both transmitter and receiver for signal coding/ encoding, scrambling/descrambling, signal alignment, signal sorting and control. Another important signal efficiency enhancement procedure is the use of electrical digital to analog converter (DAC) at the transmitter and receiver [43]. DAC usage also comes with some degree of nonlinearity and power greediness that can limit their usefulness for multi-level modulation scheme like PAM-4 in a cost effective system [48]. If nonlinearity of signal is not eliminated or reduced, it usually leads to signal distortion, which will require additional pre-distortion management procedures such as static pre-distortion (SPD) and dynamic pre-distortion (DPD) for non-linearity compensation [49]. The digital signal processing (DSP) for distortion and dispersion compensation as presented in [49, 50] to eliminate power fading high-frequency signals have further complexity in conventional PAM-4 signal generations that contradict 5G requirements for low cost signal generation approaches.

In [51], feedforward equalizer (FFE) and decision feedback equalizer (DFE) are employed at both transmitter and receiver to cancel the multi-level signal ISI and this is accomplished with system complexity and cost. To mitigate some of the complexity in PAM-4 signal generations in order to meet the demand for low cost, energy-efficient and low footprint demand for 5G networks, optical DAC PAM-4 signal generation was used in [44] with high tolerance to modulation nonlinearity. In terms of distance covered also, modulation through DML with high bit-rate signal shows several limitations due to the high chirp associated with its signal coupled with the lagging of lower PAM-4 eye while transmitting with high bit-rate and high modulation current [46]. Although, DML approach shows the simplest and most cost-effective measures but highly limited to low bit-rate and shot reach.

However, in our approach to eliminate these aforementioned limitations in PAM- 4 signal generation, unlike the conventional signal generation with EAM where electrical PAM-4 signal is employed to generate optical PAM-4 signal, the concept of HM approaches for NRZ signal generation we presented in [2] is further employed to generate optical PAM-4 signal. The approach is optimized in a simplified way to generate the signal for short reach transmissions without signaling, nonlinearity and CD compensation. The complete simulation setup is presented in **Figure 13**. We conducted further optimization of our HM model to design 28-GBaud PAM-4 signal and in fact, the same approach was tailored towards
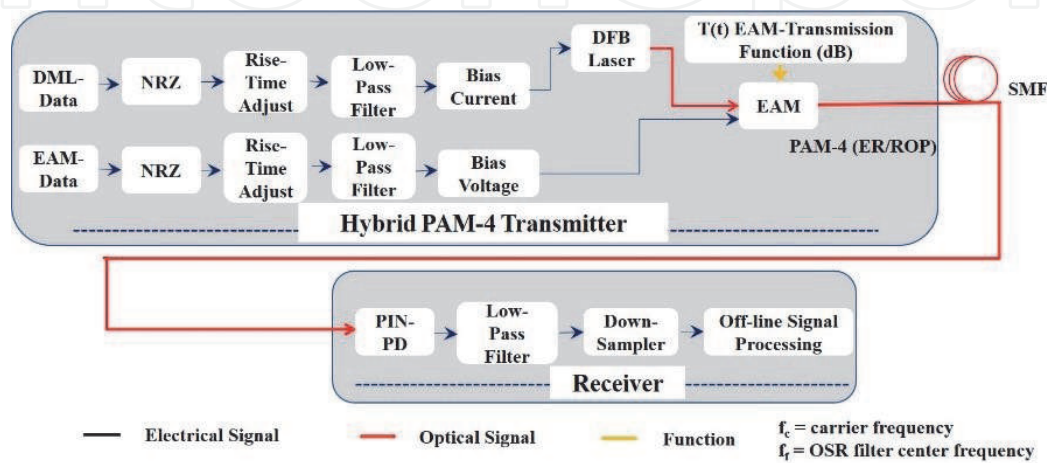


**Figure 13.**
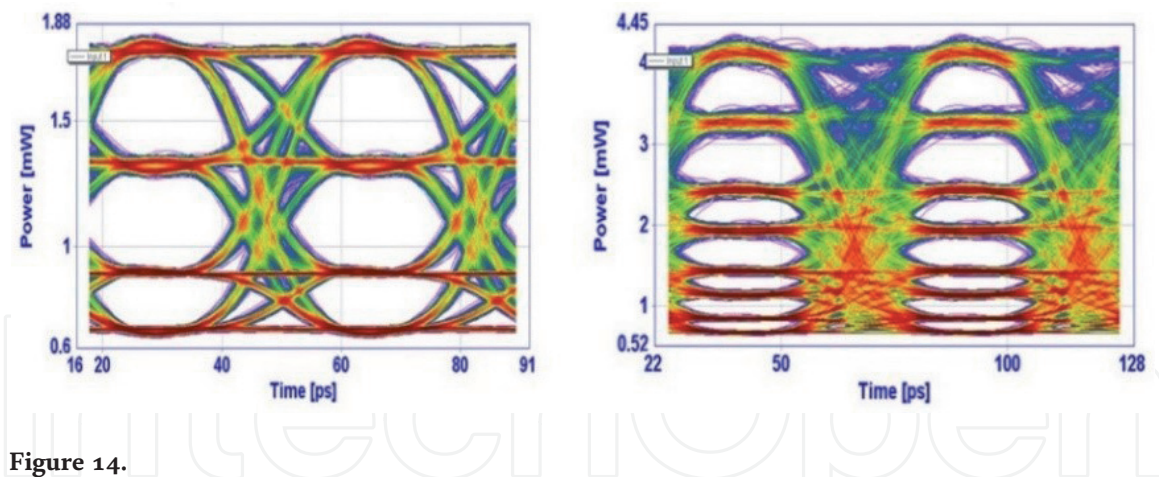*Schematic of the simplified multilevel (PAM-N) signal generation approach through HM model.*

**Figure 14.**
*Eye diagram of 28 GBaud PAM-4 and 20 GBaud PAM-8 signals generated with simplified HM approach. Here the PAM-4 signal has an ER = 4.5 dB and PAM-8 signal with ER = 7.5 dB, both signals having ROP higher than 4 dBm.*

generating a simplified 20-GBaud PAM-8 signal eliminating the conventional complexity of electrical signal coding and pulse shaping.

Both transmitters show an optical launch power of more than 4 dBm with 5 dB and 7.5 dB ER respectively. At the receiver, the multilevel signals are decoded through direct detection approach with a PIN photodetector. The eye diagrams of both PAM-4 and PAM-8 signals generated with this approach are presented in **Figure 14**. The results of transmission over 8 km of both the 28 GBaud PAM-4 and 20 GBaud PAM-8 obtained through offline digital signal processing using Gaussian approximation give error analysis below $10^{-3}$.

### 3.3 DML CML-OSR for hybrid signal compensation

The major effect of DML is the associated phase modulation to the intensity modulation, which results in CD and then ISI. In the HM model, some degree of chirp is still present in the modulated signal, which introduces limitations. With the concept of chirp managed lasers (CML) through optical signal reshaper (OSR), the transient chip from the DML can be reduced. More also, since our DML optimization earlier presented is tailored towards improving the optical signal power output and reducing the transient chirp by biasing away from the threshold. This reduces the signal ER. With the concept of CML, the ER of the DML optical signal can be optimized as well as the transient chirp. An update to the schematic in **Figure 9** is presented in **Figure 15** including a Gaussian optical filter optimized as an OSR.

The entire CML-OSR approach can be studied in [52–55]. The concept of CML decouples optical signal power and chirp of the DML signal [53], which is achieved by configuring the Gaussian filter as a band-pass filter (BPF) having a central frequency higher than the frequency of the carrier signal. This enables the filter to undergo signal edge filtering by suppressing the 1-bit while attenuating the 0-bit of the distorted NRZ optical pulse from DML. The filter is configured with a 3 dB bandwidth lower than the bandwidth of the carrier signal which distorts the signal but at the same time cut-off most of the high-frequency noises associated with the optical signal pulse. Hence, the bandwidth is highly significant to the overall performance of the OSR but care must be taken in using this approach for hybrid multilevel signal generations (e.g., PAM-4 and PAM-8) if the OSR bandwidth is further reduced or if the filter central frequency is further increased. The behavior of this approach is shown in **Figure 16** while the simulation parameter is also presented in **Table 2**. Applying this model on our generated HM optical signal
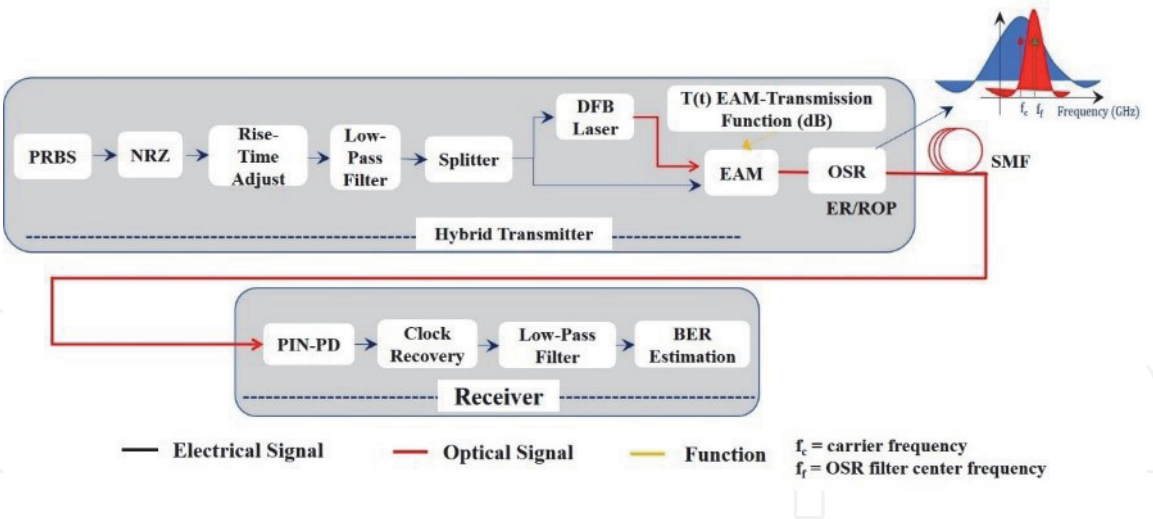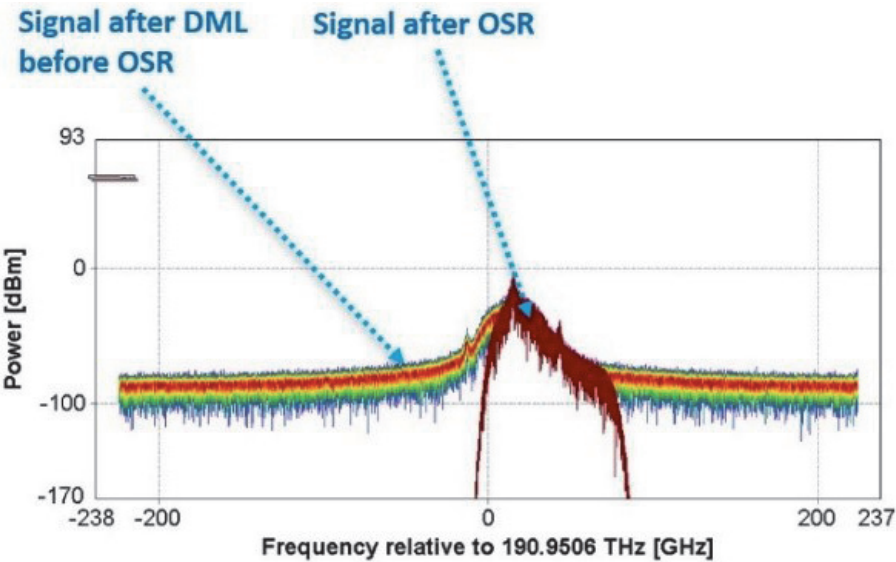
**Figure 15.**
*Hybrid simulation approach + CML-OSR.*



**Figure 16.**
*CML-OSR showing DML signals before and after OSR filtering.*

| Filter Parameters | Value |
|---|---|
| Filter Type | BandPass |
| Transfer Function | Gaussian |
| Filter Center Frequency | 190.99e12 Hz |
| Filter Bandwidth | 60 GHz |
| Gaussian Order | 4 |

**Table 2.**
*CML-OSR simulation parameters.*

improves the signal ER which further improves the overall performance of the final optical signals from the hybrid transmitter. More also, the filter significantly reduced the transient chirp associated with the DML signal. We applied this concept to both the binary and multilevel signals generated in our earlier sections and significant improvement in terms of reach was observed. With OSR, we were able

to transmit a binary 40 Gb/s HM signal beyond 40 km and both 28 GBaud PAM-4 and 20 GBaud PAM-8 signals respectively up to 10 km.

## 4. Conclusion

We have proposed and demonstrated the concept of simplified high bit-rate signal generation with a HM approach in this chapter. The current 5G and the beyond technologies specifically target such a model with less complexity but unprecedented spectral efficiency in order to reduce the capital expenditure (CAPEX) and operation expenditure (OPEX) of signal transmission and at the same time guarantee the speed requirements of the application over optical communication networks. Through simulations, we have demonstrated and shown that there is a clear path to achieve 5G backhauling without the need for CD pre and post compensation for high bitrate signal generation in short and medium reach networks. We also showed that proper optimization can improve signal launch power and eliminate the necessity of expensive optical power amplifier for high bitrate signal transmission. HM clearly simplified signal generations as we have presented in this chapter with right combination of process and components. Further research is ongoing to implement this model on a PIC so that we can perform a real-life laboratory test of the chip and investigate other areas of optimizations.

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