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Flexible MultiCAP Modulation and its Application to 850 nm VCSEL-MMF Links

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***Abstract*—In this paper we introduce a flexible scheme for the multi-band approach of carrierless amplitude phase (Flexible MultiCAP) modulation. The proposed modulation scheme can adapt to different data traffic demands and transmission link conditions, with advantages of variable bit rate and therefore power consumption adaptivity. First, simulations results are presented to show the capacity of the proposed scheme under different bandwidth restrictions, and then, as a proof of concept, its feasibility is experimentally demonstrated in 850 nm vertical-cavity surface-emitting laser (VCSEL) based transmissions over 100 m of OM4 multi-mode fiber (MMF). Data rates up to 40.6 Gb/s with spectral efficiencies up to 4 bit/s/Hz are achieved. All measured bit error rates (BERs) were below the 7% overhead forward error correction (FEC) threshold of 3.8×10^{-3}.**

***Index Terms*—Multi-band carrierless amplitude phase modulation, Optical fiber communication, Vertical cavity surface emitting lasers.**

I. Introduction

CURRENTLY, research efforts on the optical transmission do not only concentrate on higher transmission and switching rates, but also on the energy efficiency of the proposed solutions [1]–[5]. Application of the energy efficient technologies reduces the carbon footprint and operating cost. Energy efficiency and overall cost reduction is particularly important for systems with massive deployments like fiber to the home (FTTH) systems and data interconnects, with the latter applied to data transmissions in the inter- and intra-rack level. Additionally, due the accelerated growth of data traffic demands, FTTH systems and data interconnects are developing towards data rates >25 Gb/s per lane [6]–[9].

It is known that the data traffic varies in the milliseconds and hour time scale [10]. Therefore, a way to reduce energy consumption can be attained by means of variable transmission techniques that can adjust to the varying demand. While the variations in the micro scale are challenging to be exploited, due to the required system reaction time, the variations in the macro scale can form the basis for the energy consumption reduction. Several approaches on the topic have been proposed [11], [12] which include variable modulation formats, variable symbol rates, and sleep modes, e.g. optical link deactivation.

Carrierless amplitude phase (CAP) modulation has shown high energy efficiency and advantages over orthogonal frequency-division multiplexing (OFDM) and pulse amplitude modulation (PAM) with respect to power dissipation as shown in [13]. However, CAP modulation, as others modulation schemes, needs a flat frequency response of the transmission link to ensure a reliable performance. To mitigate this impairment, the multi-band approach of carrierless amplitude phase (MultiCAP) has been proposed for optical and wireless links, achieving high spectral efficiencies over large bandwidths [14]–[16]. MultiCAP modulation allows to independently choose the modulation scheme, order, baud rate, and signal power for each of its bands, achieving, with limited bandwidth components, high spectral efficiency and good performance even with a non-flat channel frequency response. In [17] a transmission technique employing MultiCAP modulation is presented, where the bandwidth of each band can be dynamically adjusted according to the requirements of optical network units (ONUs). However, only the concept is stated without any demonstration or validation of its dynamicity.

Here, we introduce and validate a flexible MultiCAP modulation that allows adjustment of the data rate to the current needs [18]. By activating and deactivating the MultiCAP sub-bands, the total bit rate of the transmission system can be adjusted for different traffic demands. Further, the modulation scheme within a given band can be also adjusted, and unlike traditional MultiCAP modulation, each band may have a different baud rate. The proposed system can not only adjust to the varying traffic demand but also to the transmission link conditions, e.g. lower baud rates have higher tolerance to the transmission impairments such as chromatic

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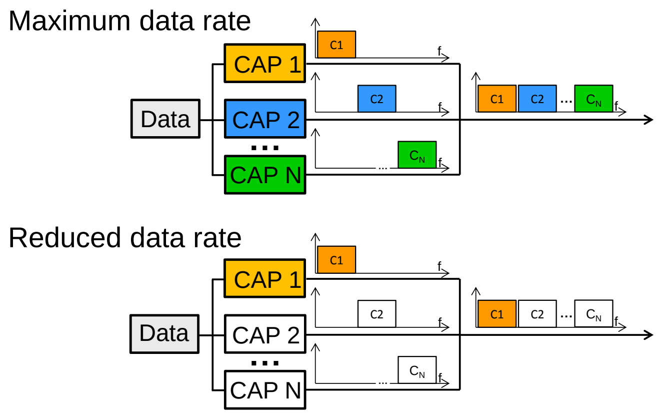

Fig. 1. Flexible MultiCAP modulation principle of operation.

dispersion, therefore longer transmission links can be bridged. Data rate flexibility can be translated into energy savings since each transmission band can be supplied by a separate transmitter and receiver sub-blocks. Therefore an adaptive transmission link is achieved, where by switching off bands, when the traffic demand is low, the energy consumption of the system is reduced. In Fig. 1 the principle of the flexible MultiCAP modulation operation is depicted. Additional energy savings can be achieved due to the fact that low data rates transmissions require lower signal power. Therefore, the transmitter launch power can be decreased.

In this paper, we introduce a flexible MultiCAP modulation concept and its application to the data interconnects. The successful performance of this flexible scheme is experimentally demonstrated for 850 nm vertical-cavity surface-emitting laser (VCSEL) based transmissions up to 40.6 Gb/s over 100 m of multi-mode fiber (MMF). Furthermore, we demonstrate that for low data rates the VCSEL bias current can be decreased contributing to the additional energy savings.

II. Experimental Setup and Digital Signal Processing

Figure 2 shows the block diagram of the experimental setup used to validate the flexibility of the proposed scheme for data interconnect applications. The transmitter consists of a 24 GSa/s arbitrary waveform generator (AWG) (Tektronix AWG7122C) with a vertical resolution of 10 bits and a 3-dB bandwidth of 5.6 GHz, a Bias-T, a DC current source, and a commercially available directly modulated 850 nm VCSEL [19]. The transmitter digital signal processing (DSP) is done offline and the generated signal samples are loaded to the AWG after quantization. After transmission through 100 m of OM4 multi-mode fiber (MMF), which has a bandwidth of 4700 MHz·km, the optical signal is converted into the electrical domain by a 22 GHz PIN photodiode (PD) with a conversion gain of 80 V/W. After conversion, the electrical signal is captured with a 33 GHz digital storage oscilloscope (DSO) at a sampling rate of 100 GSa/s and 8 bits of vertical resolution for further offline DSP. Bit error rates (BERs) are computed offline, for each band separately, from the actual received data stored with the DSO.

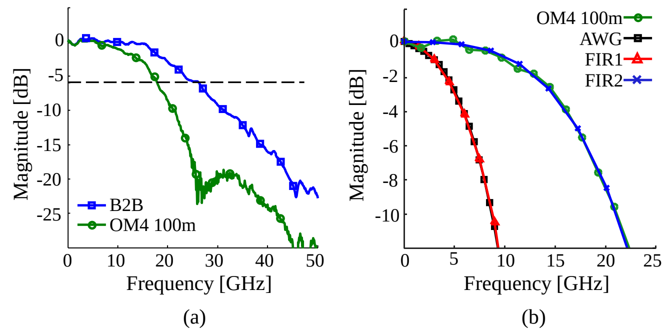

Fig. 3. (a) End-to-end frequency responses of B2B and 100 m OM4 links, and (b) comparison of frequency responses of the AWG, 100 m OM4 link, and its corresponding FIR filters used in simulations.

Figure 3(a) shows the frequency response of the back-to-back (B2B) and 100 m OM4 transmission links, measured with a 50 GHz network analyzer. These frequency responses were measured from the input of the Bias-T to the output of the PD. It is to be noted that these frequency responses are considerably flat up to 10 GHz. As a result, the AWG used in the experiments was the limiting factor of the transmissions, since it has a lower bandwidth than the end-to-end system frequency response (Fig. 3(b)).

A. Simulations and Offline Processing

The flexible MultiCAP signal is generated to make the best usage of the available bandwidth as well as assure adaptive operation. To generate the signal for each band, decorrelated pseudo-random binary sequences (PRBSs) of 2^{11}-1 bits of length are mapped into its corresponding quadrature amplitude modulation (QAM) and phase shift keying (PSK) symbol constellations, i.e. bit loading. The obtained symbol sequences are up-sampled to the number of samples per symbol determined by the baud rate of each band and filtered by the pair of CAP orthogonal filters corresponding to each band. Power loading is employed by assigning different signal amplitude weights to each band of the MultiCAP signal to mitigate the impairments due to the non-flat frequency response, e.g. frequency response of the AWG. At the receiver, after signal resampling, the in-phase (I) and

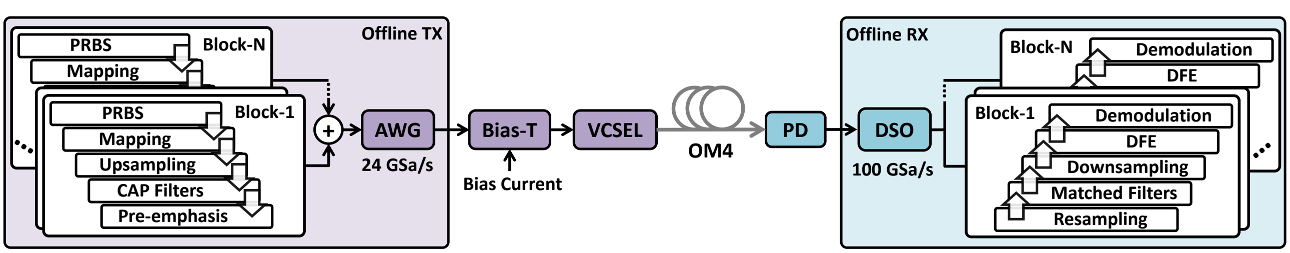

Fig 2. Block diagram of experimental setup. PRBS: pseudo-random binary sequence, AWG: arbitrary waveform generator, VCSEL: vertical cavity surface emitting laser, PD: photodiode, DSO: digital storage oscilloscope.

quadrature (Q) channels of each MultiCAP band are retrieved by filtering with filters matched to the CAP filters at the transmitter. Finally, each channel is down-sampled to construct the corresponding symbol constellations, from which the binary sequences are demodulated by means of a decision-feedback equalizer (DFE) with 30 feed-forward taps and 30 feed-back taps, and the k-means algorithm. It is to be noted that after the pre-emphasis stage at the transmitter and before the resampling stage at the receiver, the signals are quantized in accordance to the vertical resolutions of the AWG and DSO, respectively.

The main limiting factor to achieve high data rates is the frequency response of the AWG, which is considerably lower than the end-to-end frequency response of the link as can be seen in Fig. 3(b). To include these frequency responses in the simulations, linear-phase finite impulse response (FIR) filters are designed to match them. In Fig. 3(b) is shown the comparison of the frequency responses of the AWG, the 100 m OM4 link, and the designed FIR filters. To show the full capacity of MultiCAP modulation, first simulations are performed only considering the frequency response of the end-to-end 100 m OM4 link, and then, to simulate the conditions of the real experimental setup, further simulations are performed including the AWG frequency response.

In simulations, the generated MultiCAP signals are filtered by the FIR filters in order to determine suitable parameters for the MultiCAP signaling. First simulations are focused on showing the potential high bit rates that can be achieved by means of MultiCAP modulation, while showing its flexibility to adjust the modulation schemes and baud rates of each band. Assuming a generator with the same sampling frequency as the DSO used in the experiments, i.e. 100 GSa/s, and the frequency response of the 100 m OM4 link, a bit rate over 100 Gb/s is achieved with a BER below the commercial 7% overhead forward error correction (FEC) threshold of 3.8×10^{-3}. In Fig. 4 is shown the spectrum of the transmitted signal including the link frequency response, the power loading applied to the bands, and the symbol constellations of all bands as insets. Table I summarizes the main parameters of the 102.75 Gb/s generated signal. Seven bands are allocated using a total bandwidth of 23.1 GHz. It is to be noted that, as the frequency increases the signal-to-noise ratio (SNR) worsens due to the roll-off of the link frequency response. As consequence, for low frequencies where the frequency response is fairly flat and the gain is higher, high modulation orders can be employed, e.g. 128-QAM, and for high frequencies where the bandwidth constraints are more noticeable, low-order modulation schemes must be employed to ensure a good performance of the link, e.g. QPSK. To avoid the crosstalk between adjacent bands, a guard band corresponding to the sum of the 1% of the adjacent bands baud rate is left between the bands, e.g. the guard band between band 1 and band 2 is 0.01×1.25 + 0.01×2 = 0.02325 GHz.

To simulate the real experimental setup conditions, i.e. a 3-dB bandwidth of 5.6 GHz and required bit rate and modulation adjustability, an adequate tradeoff between performance and the number of bands is achieved with 5 bands. Table II shows the parameters found for each band which maximizes the bit rate. As in previous simulations, to avoid the crosstalk between adjacent bands the same percentage is used to determine the guard bands, and the modulation orders of the bands are decreased in accordance to the frequency response of the link. Furthermore, with the selected baud rates for each band, bit rates between 6 Gb/s and 10 Gb/s were achieved. By switching on and off the appropriate bands 6, 15, 28.6, and 40.6 Gb/s total data rates can be achieved. Figure 5 shows the simulation signal spectrum at the transmitter when all bands are active, including power loading and as insets the symbol constellations of all bands with which the BERs of each band

TABLE I
102.75 GB/S SIGNAL PARAMETERS

Band	Baud Rate [Gbaud]	Modulation Scheme	Bit Rate [Gb/s]	Central Frequency [GHz]	Weight (Amplitude)
1	1.25	128-QAM	8.75	0.6375	√2
2	2	64-QAM	12	2.2950	1
3	2	64-QAM	12	4.3350	1
4	2.5	64-QAM	15	6.6300	√1.2
5	5	32-QAM	25	10.4550	√1.2
6	5	16-QAM	20	15.5550	√1.2
7	5	QPSK	10	20.6550	1

TABLE II
40.6 GB/S SIGNAL PARAMETERS

Band	Baud Rate [Gbaud]	Modulation Scheme	Bit Rate [Gb/s]	Central Frequency [GHz]	Weight (Amplitude)
1	1	64-QAM	6	0.5100	1
2	1.5	64-QAM	9	1.7850	√2
3	2	32-QAM	10	3.5700	√2
4	2.4	16-QAM	9.6	5.8140	√3
5	3	QPSK	6	8.5680	√2

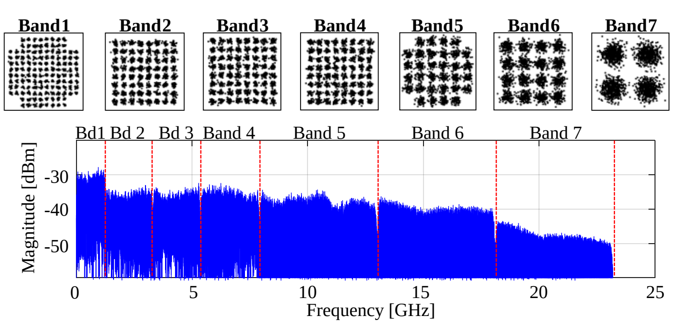

Fig. 4. MultiCAP 102.75 Gb/s signal electrical spectrum at the transmitter and symbol constellations.

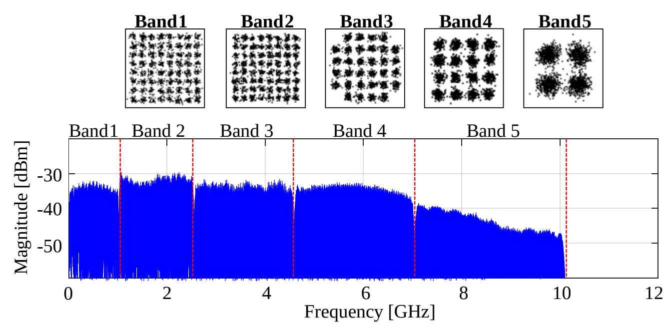

Fig. 5. MultiCAP 40.6 Gb/s signal electrical spectrum at the transmitter and symbol constellations.

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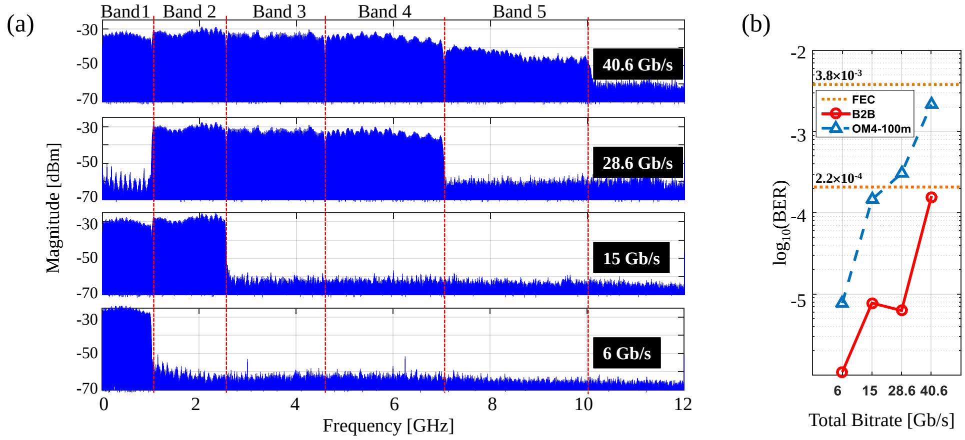

Fig 6. Fixed modulation scenario, (a) received spectra, and (b) measured BER versus total bit rate.

TABLE III
FLEXIBLE MULTICAP MODULATION PARAMETERS IN FIXED MODULATION SCENARIO

Band	Baud rate [Gbaud]	Modulation Order [M-QAM]				Bit Rate [Gb/s]			
		Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
1	1	64		64	64	6		6	6
2	1.5	64	64	64		9	9	9	
3	2	32	32			10	10		
4	2.4	16	16			9.6	9.6		
5	3	4				6			
TOTAL						40.6	28.6	15	6

were below the commercial 7% overhead FEC threshold. It can be noticed the different bandwidth occupied by each band and the different value of power of each band due to power loading technique. For the highest bit rate case, the total signal bandwidth is 10.1 GHz, with a spectral efficiency of 4 bit/s/Hz.

By increasing considerably the number of taps of the DFE, it is possible to further decrease the BER below more recent FEC threshold standards such as 2.2×10^{-4} (e.g. 400GBase-DR4). However, the complexity of the system increases at a rapid pace with the number of taps, therefore a DFE with a low number of taps is used to compute the BER results in the experiments.

III. TRANSMISSION EXPERIMENTS

The operation of the proposed scheme was investigated in two different scenarios. The first scenario was examined by activating and deactivating bands, while maintaining the modulation orders of the bands unchanged. Four different cases were implemented with bit rates of 40.6, 28.6, 15 and 6 Gb/s, respectively. In all cases, the VCSEL bias current was 4 mA and the driving voltage was 0.7 V_{pp}. In Table III a summary of the main parameters for each case is presented. The shades in the table indicate when a band is inactive for a particular case. In Fig. 6 the received signal spectra generated from the DSO captured data and the BER results are shown for the four different cases. In Fig. 6(a) activation and deactivation of the bands is clearly visible. It can be seen in Fig. 6(b) that, in all cases, the average BER of all bands is below the 7% FEC limit, proving excellent operation of the proposed concept.

In the second scenario, not only the selected bands were activated and deactivated, but also the modulation order for a given band as well as the VCSEL bias current were adjusted. Since low-order modulation schemes can tolerate a lower SNR, lower signal powers can be provided to the receiver and still achieve a successful transmission. Therefore the VCSEL bias current can be reduced, which contributes to the further transmission system energy savings. In this scenario, four different cases were studied. In Table IV a summary of the main parameters for each case is presented, and Fig. 7 shows the received electrical spectra. Activation and deactivation of the appropriate bands is visible. Figure 8(a) shows the measured BER as function of the received optical power, and Fig. 8(b) as a function of the bias current. It is to be noted that the received optical power was adjusted only by adjusting the VCSEL bias current, thus the power values in Fig. 8(a)

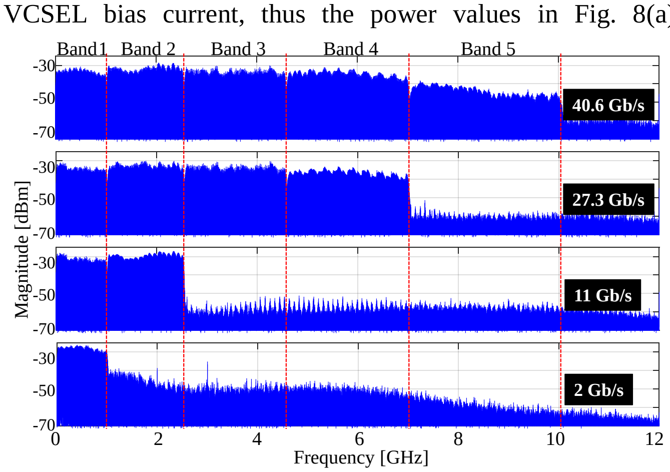

Fig. 7. Spectra for different cases in the variable modulation order scenario.

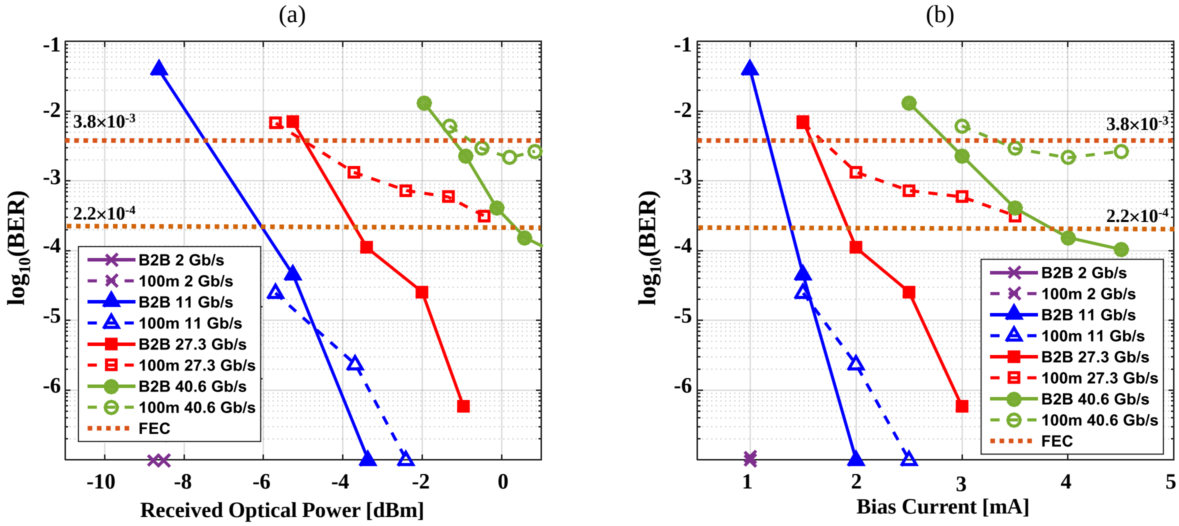

Fig 8. (a) BER versus received optical power, and (b) BER versus bias current for different bit rates and MMF lengths.

TABLE IV
FLEXIBLE MULTICAP MODULATION PARAMETERS WITH VARIABLE MODULATION

Band	Baud rate [Gbaud]	Modulation Order [M-QAM]				Bit Rate [Gb/s]			
		Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
1	1	64	32	32	4	6	5	5	2
2	1.5	64	32	16		9	7.5	6	
3	2	32	32			10	10		
4	2.4	16	4			9.6	4.8		
5	3	4				6			
TOTAL						40.6	27.3	11	2

correspond to the bias current values in Fig. 8(b). In all transmission cases, i.e. with different bit rates as well as the B2B and 100 m MMF length, operation below the 7% FEC limit was observed proving excellent operation of the system.

IV. Discussion

For both scenarios, the performance of our proposal was validated with BERs below the commercial 7% overhead FEC threshold of 3.8×10^{-3}. For more stringent FEC thresholds of recent standards, e.g. 2.2×10^{-4}, only B2B transmissions and lower bit rates transmissions over 100 m of MMF are compliant. The performance of the transmissions can be further improved at the cost of increasing the complexity of the receiver, e.g. increasing the number of equalization taps.

For the first scenario, it was noted that the guard band that was left between the first and the second band is not enough to ensure the best performance for high modulation orders, i.e. 64-QAM. As can be noted in the B2B results (Fig. 6(a)), in the 28.6 Gb/s transmission only one band with 64-QAM modulation is active, i.e. second band, while in the 15 Gb/s transmission two consecutive bands with 64-QAM modulation are active, i.e. first and second band. Therefore, the performance of this last transmission is worst even if the bit rate is lower. Contrary to the B2B case, after 100 m of OM4 MMF, the impairments of the transmission, e.g. inter-modal dispersion, are more dominant than the crosstalk effects within the bands. Therefore, for 100 m OM4 MMF transmissions the performance of the 15 Gb/s transmission is better than the 28 Gb/s transmission.

In the second scenario, in the second set of measurements (Fig. 8(b)), for a given transmission case, the VCSEL bias current was adjusted (decreased) to reach operation in proximity to the FEC limit. As can be noticed, for each transmission case, the bias current could be significantly reduced, while preserving operation below FEC threshold, e.g. for the 40.6 Gb/s 100 m transmission the current could be reduced from 4.5 to 3.5 mA, and for the 11 Gb/s 100 m transmission from 2.5 to 1.5 mA. Figure 9 shows the actual and the normalized (to 3.5 mA) VCSEL bias current versus the bit rate for the 100 m link, for which the BER is still below 7% FEC limit. By having as reference the 40.6 Gb/s transmission, when transmitting 27.3, 11, and 2 Gb/s the bias current of the VCSEL was reduced 1.75, 2.33, and 3.5 times (57.14%, 42.85%, and 28.57%), respectively. Thus, the optical received power was reduced by 3.22, 5.18, and 8.28 dB, respectively. The lowest transmission rates allow higher

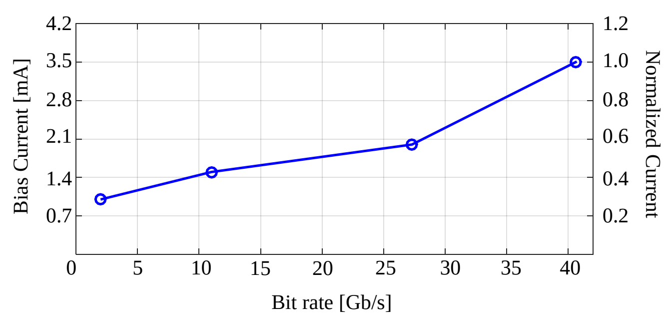

Fig. 9. Actual and normalized VCSEL bias current versus bit rate.

current reduction. Therefore, in this scenario the energy savings can not only come from activation and deactivation of the modulation/demodulation sub-blocks but also from the adjustment of the VCSEL bias current. It is to be noted that, the BERs of the 27.3 and 40.6 Gb/s transmissions over 100 m of MMF, get worse faster than the low bit rate cases since high modulation orders, i.e. 64-, 32-QAM, require a higher SNR to achieve a good performance. As well that, when the bias current of the VCSEL is close to its threshold current, i.e. < 1mA, the dominant link impairment is the VCSEL itself, since its operation point is far from the optimal one. Therefore, it was not possible to decrease the VCSEL bias current below 1 mA.

For all transmissions, the different symbol constellations were scaled, i.e. the distance between the symbols in the constellations, in order to make all of them have the same average energy. Thus, the power consumption of the bands due the modulation order is always the same. Additionally, assuming that the electronics of each sub-block are the same, and given that the VCSEL output power is linear with respect to its bias current in our range of operation [19], it is possible to approximate that the energy savings behaves linearly with respect to the number of active bands (sub-blocks).

V. Conclusion

In this paper, we propose and validate experimentally a novel flexible scheme for MultiCAP modulation. The proposed scheme offers high spectral efficiency, adjustable bit rate as well as reduced energy consumption. Simulations results validate the feasibility of the proposed scheme with bit rates over 100 Gb/s by using state-of-the-art electronics, e.g. super high-speed digital to analog converters (DACs) [20], [21]. As a proof of concept, we validate its operation in 850 nm VCSEL based data interconnect up to 40 Gb/s, showing all its key advantages. Results prove the proposed flexible MultiCAP as a prospective solution, which can be successfully applied in transmission systems that require bit rate adaptivity and energy consumption reduction.

Similarly to the study presented in [13], further research is aimed to perform a thorough comparison of the most common modulation schemes, i.e. NRZ, PAM, and OFDM, regarding bit rate adjustment and the resulting energy savings for 850 nm data interconnects.

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