Multiband Carrierless Amplitude Phase Modulation for High Capacity Optical Data Links

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Abstract—Short range optical data links are experiencing bandwidth limitations making it very challenging to cope with the growing data transmission capacity demands. Parallel optics appears as a valid short-term solution. It is, however, not a viable solution in the long-term because of its complex optical packaging. Therefore, increasing effort is now put into the possibility of exploiting higher order modulation formats with increased spectral efficiency and reduced optical transceiver complexity. As these type of links are based on intensity modulation and direct detection, modulation formats relying on optical coherent detection can not be straight forwardly employed. As an alternative and more viable solution, this paper proposes the use of carrierless amplitude phase (CAP) in a novel multiband approach (MultiCAP) that achieves record spectral efficiency, increases tolerance towards dispersion and bandwidth limitations, and reduces the complexity of the transceiver. We report on numerical simulations and experimental demonstrations with capacity beyond 100 Gb/s transmission using a single externally modulated laser. In addition, an extensive comparison with conventional CAP is also provided. The reported experiment uses MultiCAP to achieve 102.4 Gb/s transmission, corresponding to a data payload of 95.2 Gb/s error free transmission by using a 7% forward error correction code. The signal is successfully recovered after 15 km of standard single mode fiber in a system limited by a 3 dB bandwidth of 14 GHz.

Index Terms—Fiber optics communication, multiband carrierless amplitude phase modulation (MultiCAP), short range communications.

I. Introduction

DATA center links operating at lane rates of 100 Gb/s per wavelength are required in order to cope with future demands of bandwidth [1]. Link capacities as high as 400 Gb/s and even 1.6 Tbps are already projected as potential

next steps [2]. Current and upcoming standards for 100 Gb/s, such as 100GBASE-SR10, 100GBASE-SR4, and 100GBASE-LR4 are based on using ten lanes of 10 Gb/s or four lanes at 25 Gb/s each. Traditionally, the strategy for capacity upgrades has been to exploit the benefits of parallel optics and to rely on higher bandwidth availability for the electronic and optical components. However, this approach would require, e.g. 16 lanes at 25 Gb/s in order to achieve the 400 Gb/s target, thereby making it challenging to meet 400 Gb/s form-factor pluggable (e.g., CDFP2 and CDFP4) requirements on power consumption and footprint [3], [4]. Therefore, it is crucial to develop other solutions for beyond 100 Gb/s data links satisfying these industry requirements in terms of footprint, power consumption, and cost efficiency.

Advanced modulation formats have gained increasing interest from research as well as industry as a method to reduce the number of lanes while increasing the total link capacity. Recent reported experiments include 112 Gb/s half cycle - 16 level quadrature amplitude modulation (QAM) [5], and 100 Gb/s, 25 Gbaud 4 level pulse amplitude modulation (PAM) [6]. Discrete multitone (DMT) modulation has also recently been demonstrated to achieve 100 Gb/s [7]. However, all mentioned approaches require either dual polarization or a wavelength division multiplexing (WDM) scheme to achieve the claimed bitrates, and thus double the number of lanes and light source-photo detector pairs required in the system.

This paper reports on a feasible solution for the possible upcoming 400 Gb/s, four lane standards targeting 2 to 10 km reach applications. The proposed scheme employs four 100 Gb/s single wavelength, single polarization lanes. An experimental demonstration of a single lane with optical transmission over 15 km standard single mode fiber (SSMF) at a 1310 nm wavelength has been carried out. A total capacity of 102 Gb/s using a novel multiband CAP modulation (MultiCAP) signal is successfully generated, transmitted, and detected employing a link with an end-to-end 3 dB bandwidth of only 14 GHz. The bit error rate is below the 7% forward error correction (FEC) limit, corresponding to a net bitrate of 95.2 Gb/s error free transmission.

To the best of the authors knowledge, this approach achieves the highest experimental reported bitrate using CAP modulation in a single wavelength, single polarization, and direct detection optical link. By the possible extension to four lanes, these results demonstrate the prospect for 400GBASE solutions with more than 10 km reach.

The paper is structured in seven sections. Section I reviews the state of the art on short range optical links. Section II

motivates this study and introduces the concept of CAP. Section III explains how to achieve 100 Gb/s using CAP. Section IV introduces the principle of operation of MultiCAP and how it overcomes the challenges of conventional CAP. Section V presents an analytical comparison between CAP and MultiCAP based on numerical simulations. Section VI presents the experimental validation of the proposed scheme. Finally, the paper concludes with a summary of the study presented.

Fig. 1. Principle of operation of a CAP system. Data refers to a binary stream of data. *M* refers to the constellation order. *Tx* and *Rx* refers to transmitter and receiver, respectively.

Fig. 2. CAP transmitter filters for channels *I* (top) and *Q* (bottom).

II. MOTIVATION

CAP modulation is a multidimensional and multilevel modulation scheme proposed in mid 70s by Falconer *et al.* at Bell Labs [8]. CAP displays certain similarities to QAM in its ability to transmit two streams of data in parallel. In contrast to QAM, however, CAP does not rely on a carrier, but uses filters with orthogonal waveforms to separate the different data streams. This makes CAP receivers simpler than QAM receivers while achieving the same spectral efficiency and performance, a quality that made it very popular for digital subscriber lines (DSLs) during the 90s [9], [10]. As bandwidth demands raised and high speed electronics became more affordable, there were strong efforts put into exploiting the available bandwidth of deployed copper cables [11], but CAP was proven to be very sensitive to non-flat spectral channels, and required very complex equalizers [12], sacrificing the inherent simplicity of CAP. Therefore, in 1999 the international telecommunications union (ITU) deprecated it in favor of DMT [13]. By dividing the available bandwidth into many subchannels, DMT could increase total throughput and performance. Although the complexity of this scheme was still higher than in case of un-equalized CAP, the electronics needed to make it work at these bitrates were inexpensive, and DMT remains the most widely used modulation format in most asynchronous digital subscriber lines (ADSLs).

Lately, CAP has been investigated for short range optical data links [14]–[16]. One of its most attractive features for this scenario is the ability to use analog filters to generate the CAP signal, allowing for low power consumption and footprint. However, the need of a very flat frequency response of the channel inhibits its abilities to achieve beyond 100 Gb/s bitrates. In addition, a practical implementation of wide-band analog filters with linear and orthogonal phase response is very challenging. DMT could provide a solution in the same way it did for ADSL, but in this case, the electronics needed to operate at these high bitrates are still far from affordable [17], especially considering the growing high volume sales on active optical cables for data-centers [18]. We propose to use a multiband approach to CAP signalling (MultiCAP), where the CAP signal is divided into smaller subbands. Thereby, the advantages of CAP such as lower peak-to-average power ratio (PAPR) and simple implementation, can be combined with the advantages of DMT. Additionally, the CAP filters become easier to realize, since the frequency bands covered by each pair of filters are narrowed down. The viability of MultiCAP is investigated in this paper.
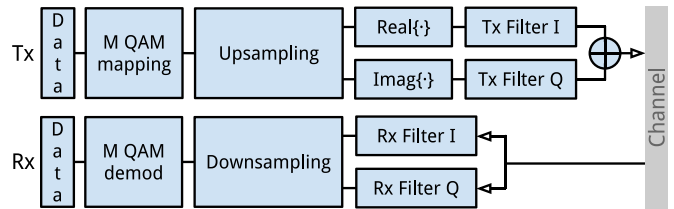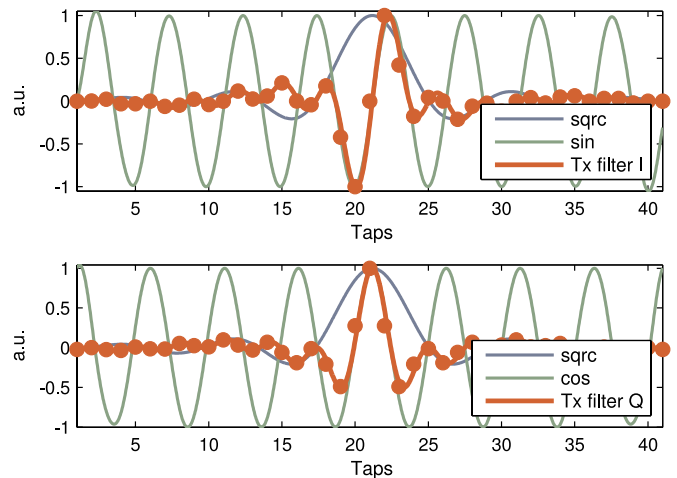
III. 100 GB/S CAP PRINCIPLE OF OPERATION

Fig. 1 shows the principle of operation of a conventional CAP system. In order to achieve 100 Gb/s by using this principle, we start with a stream of data generated from a pseudo-random bit sequence (PRBS) length of $2^{11} - 1$ bits, which is repeated eight times to achieve a total 2^{14} bits. This is encoded into a 16-QAM constellation using gray coding. The number of samples per symbol is given by the ratio between the sampling frequency and the symbol rate. At least three samples per symbol are required for a CAP signal to be sampled without losing spectral information; which means that the sampling frequency of the system must be above 75 GSa/s for a 25 Gbaud signal. After the binary sequence has been mapped into the constellation, the *I* and *Q* channels can be extracted by taking the real and imaginary parts of the signal.

The next step is the orthogonal filtering. Fig. 2 shows the two orthogonal filters composed by the time-domain multiplication of a root raised cosine (RRC) and a sine/cosine for channels *I* and *Q,* respectively. There are three parameters that characterize such a filter: the sine and cosine frequency, the roll off factor, and the filter length. The frequency of the sine and cosine determines the frequency band at which the signal is transmitted. A particular property of this parameter is that, if set to an integer multiple of the symbol rate, a conventional QAM receiver can be employed [19]. Otherwise, the frequency can be arbitrarily chosen as long as it is higher than the highest frequency of the RRC. The roll off factor α determines the excess of bandwidth. Since
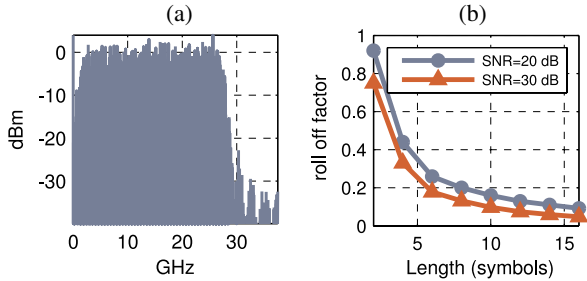
Fig. 3. (a) 100 Gb/s CAP signal spectrum. (b) Roll off factor versus filter length for a BER of 10^{-9} under different SNR conditions.
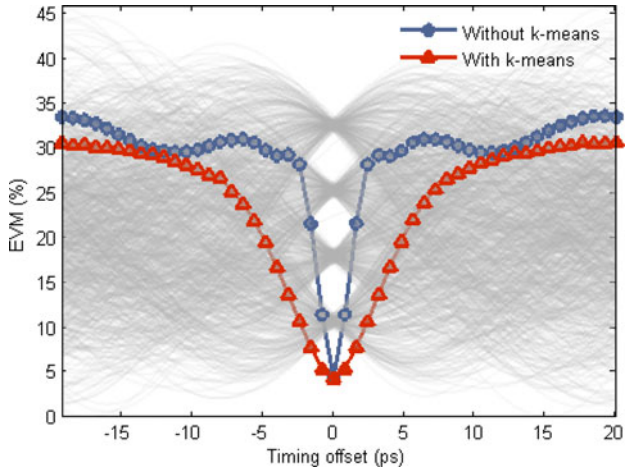

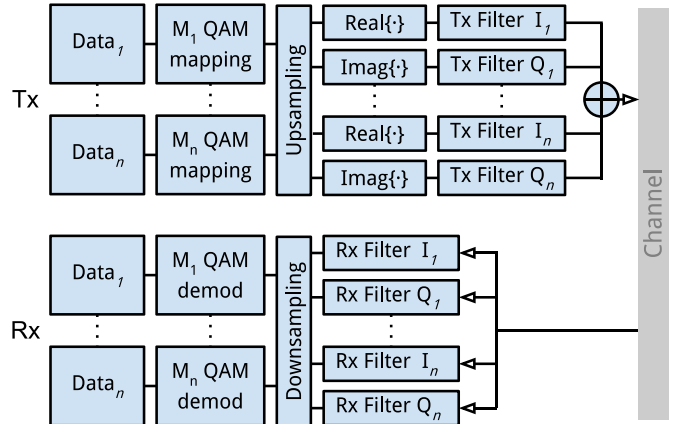Fig. 4. Effect of timing offset in a CAP system.

Fig. 5. Principle of operation of a MultiCAP system.

rotation. For this reason, we use the k-means algorithm [22] to enhance not only the tolerance towards timing offset but also the optimization of the decision thresholds [23].

In comparison to DMT, CAP is shown to offer advantages in SNR requirements and robustness to multipath interferences [24]. Additionally, (de)modulation can be implemented using electrical filters without the need for carrier recovery, frames or adaptive equalization.

IV. 100 GB/S MULTICAP PRINCIPLE OF OPERATION

The MultiCAP operation principle is illustrated in Fig. 5. The principle relies on breaking the signal into independent subbands occupying different frequency bands. Thereby, the modulation order and signal power can be tailored to the SNR in each subband. This effectively overcomes an important drawback of conventional CAP, namely the need of a flat frequency response of the channel, while increasing the flexibility of the total throughput.

Another relevant advantage of MultiCAP in systems employing digital signal generation is a relaxation of the requirement for the digital-to-analog converter (DAC). Let us define $F_{s,\mathrm{Nyquist}}$ as the minimum sampling frequency at which a MultiCAP signal can be recovered, and $F_{s,\mathrm{tx}}$ the sampling frequency at which a MultiCAP signal is generated:

$$\begin{cases} F_{s,\mathrm{Nyquist}} > 2R_s(1+\alpha) \\ F_{s,\mathrm{tx}} = \dfrac{1}{N}R_s N_{\mathrm{ss}} \end{cases}$$

where R_s is the total symbol rate that we aim to transmit, α is the roll-off factor of the CAP filters, N is the number of subbands, and N_{ss} is the number of samples per symbol for all subbands. N_{ss} must be chosen so that $F_{s,\mathrm{tx}} > F_{s,\mathrm{Nyquist}}$. This resolves to the condition:

$$N_{\mathrm{ss}} > 2N(1+\alpha).$$

For sufficiently low α values, it is possible to reduce the total sampling rate while keeping the same total baudrate. Table I gathers examples of this concept with several MultiCAP configurations. Note how the requirement on the sampling rate $F_{s,\mathrm{tx}}$ is reduced from 75 GSa/s for single band CAP to 62 GSa/s by

we are considering pass-band RRC filters, the total pass-band bandwidth of the CAP signal is $(1+\alpha)$ times the baud rate. The closer α approaches to zero, the closer the frequency response of the RRC can be approximated to a rect($\cdot$) function and the bandwidth is most efficiently utilised. However, this implies a higher PAPR as well as a larger number of taps [20]. The filter length is a critical parameter to both performance and complexity of the system. The lower the length of the filter, the simpler. On the other hand, it requires higher roll-off factor in order to keep the same performance. Fig. 3(a) shows the spectrum of a CAP signal sampled at 75 GSa/s with a central frequency of 14.5 GHz, a roll off factor of 0.15, and a filter length of ten symbols. Fig. 3(b) shows the roll off factor as a function of the filter length required to achieve a BER of 10^{-9} for SNRs of 20 and 30 dB. The BER was estimated from the error vector magnitude provided by the constellation [21]. After the filtering, the signals from the two channels are added and transmitted.

At the receiver end, inverted matched filters separate the two channels and the two orthogonal signals can be recovered. Fig. 4 shows the eye diagram of one of the channels after the filter, along with an analysis of the timing offset. One of the disadvantages of using CAP signals is the reduction in the horizontal eye opening. This is a consequence of not having a carrier to transport the data. Since there is no down-conversion to baseband, demodulation process takes place in pass-band, and hence the closed horizontal eye opening. Notably, simulations show that the main effect of timing offset in a CAP signal is constellation

TABLE I
MULTICAP EXAMPLES FOR LOWERING THE REQUIRED SAMPLING RATE FOR SIGNAL GENERATION

N	Rs (Gbaud)	α	Nss	$F_{s,tx}$ (GSa/s)	$F_{s,Nyquist}$ (GSa/s)
1	25	0.2	3	75	60
2	25	0.2	5	62.5	60
4	25	0.2	10	62.5	60
4	25	0.1	9	56.25	55
5	25	0.1	11	55	55

Fig. 6. Optical simulation setup.

simply adding an additional band. However, four bands would not further reduce it unless the α is reduced to 0.1; in which case we observe that a five band configuration can have a sampling rate equal to the Nyquist sampling frequency. Hence, a high up-sampling factor can be used while the required sampling rate is kept at a value that is closer to the Nyquist sampling frequency.

V. PERFORMANCE SIMULATIONS

In this section we show the performance improvement of MultiCAP over traditional CAP by simulating the two previously discussed solutions under the same optical conditions. The optical simulations are enabled by VPItransmissionMaker.

A. Simulation Setup

The schematics of the simulation is shown in Fig. 6. The transmitter is composed of an import module, a Gaussian filter, and an externally modulated laser (EML). The link is simulated with a SSMF. The receiver is modeled with an optical attenuator, a photo-diode (PD), and an export module. The input of import module is a text file generated in Matlab containing the samples that represent the MultiCAP signal. The output of the module is the electrical signal, which is filtered with a first order Gaussian filter of 25 GHz 3 dB bandwidth in order to simulate the electrical bandwidth limitations of the transmitter. The EML converts the electrical signal into the optical domain at a 1310 nm wavelength. The EML is modeled with a relative intensity noise (RIN) value of –160 dB/Hz and 100 KHz of linewidth. Dispersion and attenuation values for SSMF are disabled by default. After 1 km of transmission, the signal is photo-detected by a PD that is modeled with a responsivity value of 0.75 A/W and a thermal noise current of 30 pA/$\sqrt{\text{Hz}}$. Finally, the signal is exported as a text file and processed in MATLAB. The parameters used for both MultiCAP and CAP are summarized in Table II.

The BER of a CAP band is estimated from the error vector magnitude provided by the constellation [21]. The BER of the MultiCAP system is provided as the average of the BER of the individual bands.

B. Simulation Results

Fig. 7 provides a comparative analysis of how MultiCAP performs with respect to conventional CAP regarding received optical power, bandwidth, chromatic dispersion, and RIN. We define

TABLE II
SIGNAL PARAMETERS FOR THE SIMULATION

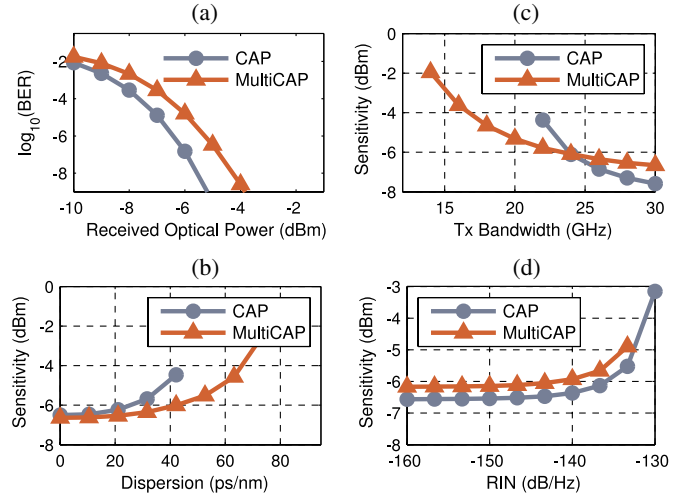|	CAP	MultiCAP
Number of Bands	1	6
Baudrate (Gbaud)	25	4.26
Modulation order	16	16
Line Rate (Gb/s)	100	102.4
Samples per symbol	3	15
Sampling frequency (GSa/s)	75	64
Filters length (symbols)	10	10
Filters roll-off	0.15	0.15

Fig. 7. (a) BER curves, (b) transmitter bandwidth tolerance, (c) chromatic dispersion tolerance, and (d) RIN tolerance.

the sensitivity as the minimum acceptable value of received optical power needed to achieve a BER of 10^{-3}. Fig. 7(a) presents the BER as a function of the received optical power when there are no bandwidth restrictions at the transmitter (the Gaussian filter is disabled). We can observe that MultiCAP suffers 1 dB of penalty in the sensitivity with respect to CAP. Fig. 7(b) shows the sensitivity degradation of both schemes when the bandwidth of the transmitter is swept from 30 to 12 GHz. While CAP cannot tolerate channel bandwidths below 22 GHz, MultiCAP is able to tolerate a 3 dB bandwidth as low as 14 GHz. In comparison, single band CAP proves to perform better provided that the bandwidth is higher than 24 GHz (note that these simulation results do not take advantage of bit loading or power loading, since all bands are set to the same power level and the same modulation order (16-CAP) for comparison purposes). Fig. 7(c) shows the tolerance of both signals towards chromatic dispersion values ranging from 0 to 80 ps/nm. In this case, MultiCAP proves to tolerate up to 35 ps/nm more chromatic dispersion than conventional CAP. Fig. 7(d) shows the tolerance toward the RIN value of the laser source. In this case, conventional CAP shows a constant gain of 0.4 dB over MultiCAP.

C. Discussion

A simulation analysis between conventional CAP and the proposed MultiCAP signaling shows that MultiCAP outperforms
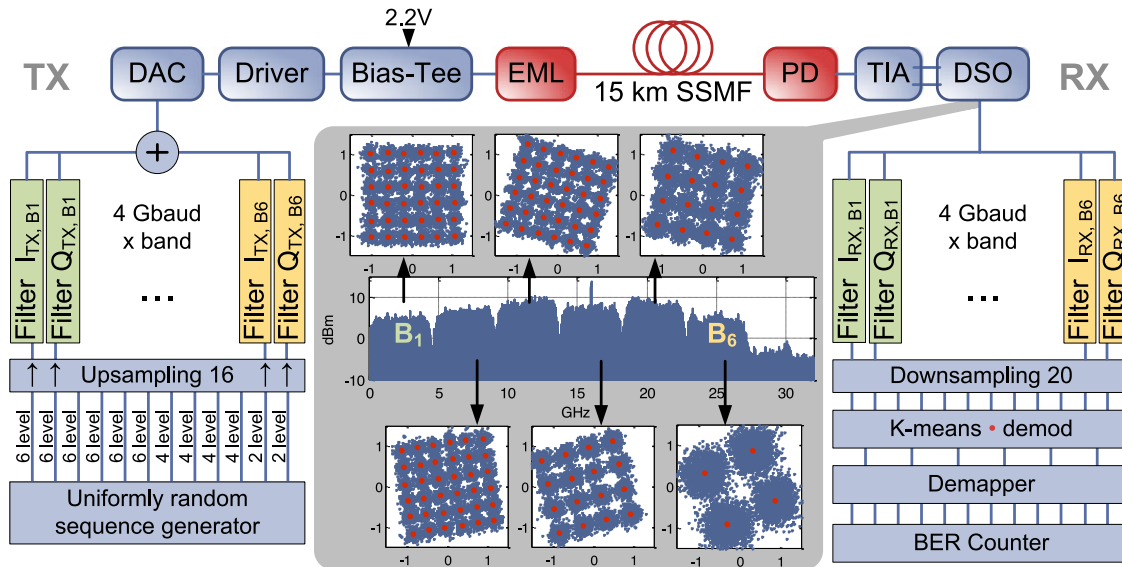
Fig. 8.   Experimental setup. DAC, EML, PD, and DSO.

conventional CAP in systems limited by bandwidth and dispersion. MultiCAP is able to maintain the line rate at the same sensitivity as in CAP in 22% less bandwidth. This is because the SNR is sufficiently flat across each of bands, as compared to the single band CAP case. Regarding of chromatic dispersion, MultiCAP can tolerate values up to 50% larger than CAP is able to do. This is attributed to the fact that for a single CAP band at 25 Gbaud, the symbol period is 20 ps; whereas for a six bands CAP, the symbol period is englarged to six times more. Moreover, in transmission links whose performance is mainly limited by low SNR, our results shows that conventional CAP offers a constant gain of 1 dB. This is induced by inter-band-interference. Given the advantages in terms of reduced bandwidth requirements and dispersion tolerance, we conclude that MultiCAP is a better candidate for short range optical links, in which multi-mode fiber is often used in combination with directly modulated lasers (DMLs), resulting in highly dispersive and bandwidth limited channels with low attenuation.

VI. EXPERIMENTAL VALIDATION

In order to verify the results obtained in the previous section, an experiment that tests a 102.4 Gb/s MultiCAP signal over 2, and 15 km of SSMF was successfully executed.

A. Experimental Setup

The MultiCAP solution and experimental setup used in the experimental demonstration is illustrated in Fig. 8. The main building blocks are a transmitter comprising a DAC, a driver amplifier, a bias-tee, and an EML; a 15 km SSMF link; and a receiver consisting of a PIN PD with a trans-impedance amplifier (TIA) and an 80 GSa/s digital storage oscilloscope (DSO). Signal generation and demodulation is performed off-line using MATLAB. For the signal generation, 12 data sequences of 16384 randomly generated symbols are generated with modulation orders from 2 to 6 according to the desired modulation

orders in the individual MultiCAP subbands. The 12 symbol sequences are upsampled to 16 Sa/symbol and filtered by the six pairs of MultiCAP subband transmitter filters. The filters are finite impulse response (FIR) filters with a length of ten symbols each. The roll-off factor used for the transmitter and receiver CAP filters is 0.15, and the frequencies of the sines and cosines that make up the CAP filters are spaced 4.56 GHz apart, starting at 2.3 GHz in the first band. The modulation orders for each band were chosen to be 36-QAM for the first three bands, 16-QAM for the next bands bands, and 4-QAM for the last band. This was empirically chosen to best fit the available SNR at that specific frequency band. The combined 102 Gb/s MultiCAP signal is generated by adding the outputs of the six filter pairs. By adjusting the weights of each pair of filters, the non-flat frequency response of the channel is pre-compensated. The signal generation is performed in MATLAB, and used to drive a 64 GSa/s DAC with an effective resolution of 5 bits. The DAC output is amplified to a peak-to-peak voltage of 2 V and used to drive a 1293.55 nm integrated distributed feedback laser - electro-absorption modulator (DFB-EAM) with the 3-dB bandwidth of 20 GHz. The signal from the DFB-EAM is propagated through a 15 km SSMF link with a total link loss of 7 dB. Launch power is 5 dBm. The optical spectrum back to back (B2B) and after transmission is shown in Fig. 9(b). The end-to-end channel frequency response is measured by performing a discrete frequency sweep with the DAC and shown in Fig. 9(a) along with the spectrum of the pre-compensated 6-band MultiCAP signal normalized with respect to its maximum. We can observe that the 3-dB bandwidth of the channel is 14 GHz, while the signal occupies a total bandwidth of 28 GHz.

After photodetection, the signal is sampled and stored by the DSO for off-line processing. The signal is demodulated by filtering with a time inverted version of the transmitter filters. After filtering, the signals are down sampled, and the two orthogonal components of the six bands can be obtained to construct the received constellation diagrams shown as inserts in Fig. 1
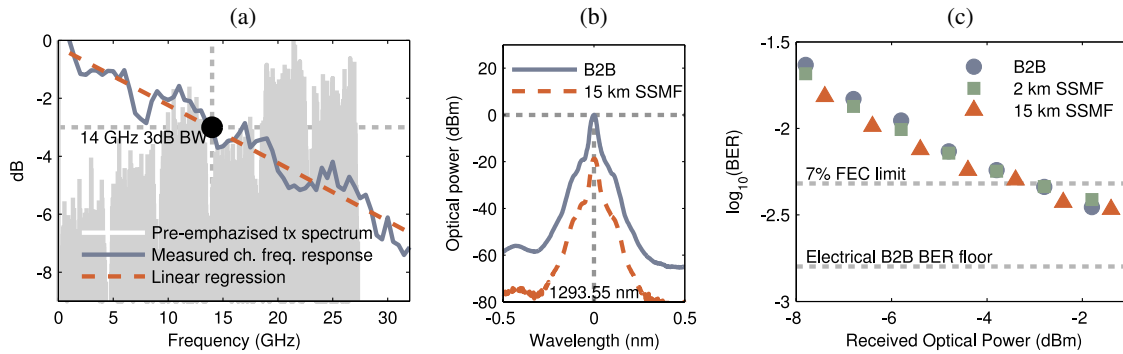
Fig. 9. (a) Frequency response pre-DAC signal spectrum, (b) optical spectrums, and (c) BER curves.

together with the received spectrum. Demodulation and compensation for constellation rotation and asymmetry caused by local non-flat in-band spectral response is performed employing the k-means algorithm [22].

B. Experimental Results

Fig. 9(c) shows the measured BER as a function of the received optical power B2B and after 2 and 15 km SSMF transmission. Receiver sensitivity at the 7%-overhead FEC limit of $4.8 \cdot 10^{-3}$ is -3.3 dBm in all cases, and no signal degradation or power penalty is observed from the transmission. This is in agreement with the simulation results observed in Fig. 7, where the sensitivity at 14 GHz is around -2 dBm without power or bit loading and negligible penalty is observed up to 20 ps/nm of chromatic dispersion. Due to the limited effective resolution of the DAC [17], a BER floor of the electrical signal driving the EML is measured at $1.5 \cdot 10^{-3}$. The advantages of the MultiCAP approach, including the ability for channel response pre-compensation, reduced DAC sampling rate requirements, and tailoring of the modulation order to the SNR of the individual subbands are clearly observed, as these are exactly the features that enable the generation of the 102.4 Gb/s signal using a 64 GSa/s DAC and transmitting it over an channel with an end-to-end 3 dB bandwidth of 14 GHz.

VII. CONCLUSION

A novel approach named MultiCAP has been proposed as a solution for beyond 100 Gb/s short range optical data links. Numerical simulations have been performed showing significant improvements for bandwidth and dispersion limited channels, over traditional CAP, while showing comparable tolerance toward SNR. Furthermore, the complexity of the transceivers in terms of hardware requirements is reduced regardless using a digital or analog implementation by either reducing the sampling frequency, or reducing the bandwidth requirements of the analog filters respectively. However, there is an increase of complexity derived from the multi-band architecture, from where the increase in performance is obtained. A tradeoff between performance and complexity must be considered for different applications. The principle has been experimentally demonstrated by realizing a 15 km optical link with a total bitrate of 102 Gb/s using only a single wavelength and direct detection.

In the reported experiment, assuming FEC encoding an effective bitrate of 95.36 Gb/s is achieved. Despite the use of a high speed (64 GSa/s) DAC, the signal generation relies on the use of transversal filters in order to maintain a level of simplicity in the digital signal processing. By extending these results to four lanes, the prospects of 400 Gb/s optical interconnect have been demonstrated for next generation client side data links.

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