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Carrierless amplitude phase modulation of VCSEL with 4 bit/s/Hz spectral efficiency for use in WDM-PON

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Abstract: We experimentally demonstrate successful performance of VCSEL-based WDM link supporting advanced 16-level carrierless amplitude/phase modulation up to 1.25 Gbps, over 26 km SSMF with spectral efficiency of 4 bit/s/Hz for application in high capacity PONs.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

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1. Introduction

The increasing bit-rate per user demand in access networks requires systems that can support higher capacity. In order to satisfy the capacity needs, access networks are moving from classic spectral inefficient non-return to zero time-division multiplexing (NRZ-TDM), to wavelength-division multiplexing (WDM) and more advanced modulation formats. Moreover, the complexity raise has to be kept to the minimum in order make the system feasible for access networks. Different techniques have been used for advanced modulation, such as discrete multitone (DMT) [1], and carrierless amplitude/phase CAP [2]. For high-speed transmission, the overall CAP architecture has been demonstrated to be less complex and with better performance than DMT architecture [3]. Moreover, high-speed multilevel CAP

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implementation has been demonstrated by using transversal filters developed for equalization of NRZ data [4].

Vertical cavity surface emitting lasers (VCSELs) are especially attractive for access networks, due to their low manufacturing cost and low power consumption. Compared to edge-emitting lasers, VCSELs have inferior performance in terms of linewidth, chirp, stability and linearity. Therefore, it is important to understand and evaluate the feasibility of employing VCSELs for applications requiring higher laser performance.

Our paper proposes and experimentally demonstrates a VCSEL-based WDM system with CAP modulation for access networks. The experiment successfully demodulates 4 channels 100 GHz spacing after 26 km of SSMF. Each VCSEL is directly modulated at 1.25 Gbps in a 312.5 MHz bandwidth, corresponding to a spectral efficiency of 4 bit/s/Hz. To our knowledge, this is the first demonstration of a VCSEL based WDM CAP system. Our experiment shows the potential for using VCSELs as light sources in WDM PON, supporting spectral efficient modulation formats and operating over a modest baseband bandwidth favoring low complexity electronics.

2. CAP modulation for access networks and short-range links

Carrierless amplitude/phase modulation (CAP) is a multilevel and multidimensional modulation technique proposed by Bell Labs [5]. In contrast to quadrature amplitude modulation (QAM), CAP does not use a sinusoidal carrier to generate two orthogonal components. CAP uses two orthogonal signature waveforms to modulate the data in two dimensions. At the receiver, two filters are used to reconstruct the signal from each component. CAP is especially attractive for access networks and short-range links, as it employs low complexity electronics, and allows for narrow channel spacing due to the high spectral efficiency.

In this experiment, we have used four-level encoding for each dimension generating the so-called CAP-16. Previous publication demonstrated 8 levels encoding CAP-64 [6], 3 orthogonal components 3D-CAP [7] and working with bit-rate up to 40 Gbps [4].

3. Experimental setup

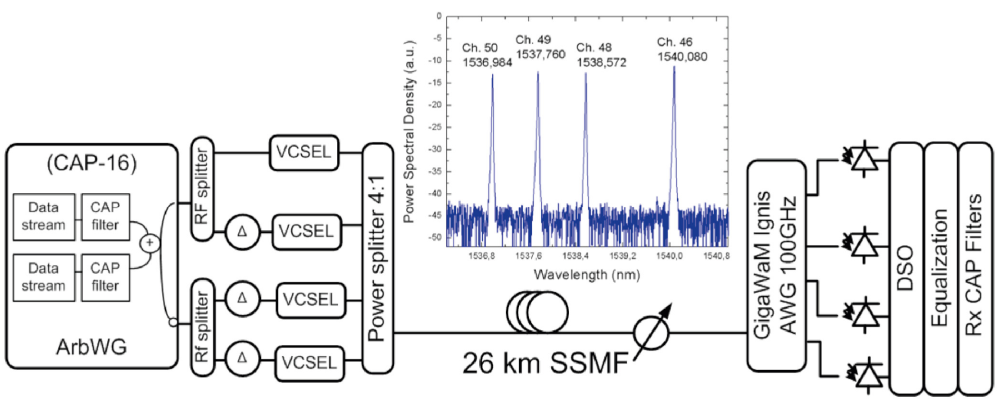

Fig. 1. Experimental Setup. Arbitrary waveform generator (ArbWG), array waveguide grating (AWG), digital storage scope (DSO).

Figure 1 shows the setup used in the proof of principle experiment. A 500 MHz-bandwidth, 1.25 Gsa/s Arbitrary Waveform Generator (ArbWG) is used to generate the CAP-16 signal at 1.25 Gbps. ArbWG features limits our CAP-16 signal up to 1.25 Gbps with an upsampling 4 to ensure no aliasing products. The ArbWG has 10-bits vertical resolution. The 2 outputs of the ArbWG are split in 2 and delayed to emulate 4 x 1.25 Gbps uncorrelated CAP signals. The minimum decorrelation between channels is 7 ns or approximately 2 bauds. Each uncorrelated

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CAP signal directly modulates a commercially available 1550 nm-wavelength, 4.5 GHz-bandwidth VCSEL from RayCan. The output power of each VCSEL is approximately -1 dBm. At the transmitter side, the four wavelengths or channels, are multiplexed with a passive optical power combiner; while at the receiver side, wavelength demultiplexing is done with an arrayed waveguide grating (AWG). The power combiner has conversion loss of 7.5 dB. The AWG has an insertion loss of 1.5 dB. The VCSELs are uncooled. The VCSELs are wavelength-tuned by tuning the bias current in order to keep wavelength spacing and fit the 100 GHz-spacing grid of the AWG. Optionally, 2 AWGs with the same grid can be used for multiplexing and demultiplexing wavelengths, resulting in 6 dB additional power margin. The system was evaluated after 26 km transmission of standard single mode fiber (SSMF), with total fiber attenuation of 7.8 dB. A variable optical attenuator is placed after the fiber for bit error rate (BER) measurements. Each channel is detected by a 10 GHz PIN photodiode and stored in a digital storage scope (DSO) for offline demodulation. The demodulation is done in Matlab by filtering the signal with 2 receiving CAP filters to reconstruct each orthogonal component.

4. Results

The VCSELs were tuned to fit the ITU channels number 50, 49, 48, and 46. The embedded graph in Fig. 1 shows the optical spectrum of the WDM-CAP signal with the corresponding wavelengths of each channel. Figure 2 shows the 65-taps CAP filters in time and frequency domain, and the electrical spectrum of the CAP signal directly from the ArbWG. The 3dB-bandwidth of each 1.25 Gbps CAP-16 is 312.5 MHz that corresponds to 4 bit/s/Hz spectral efficiency.

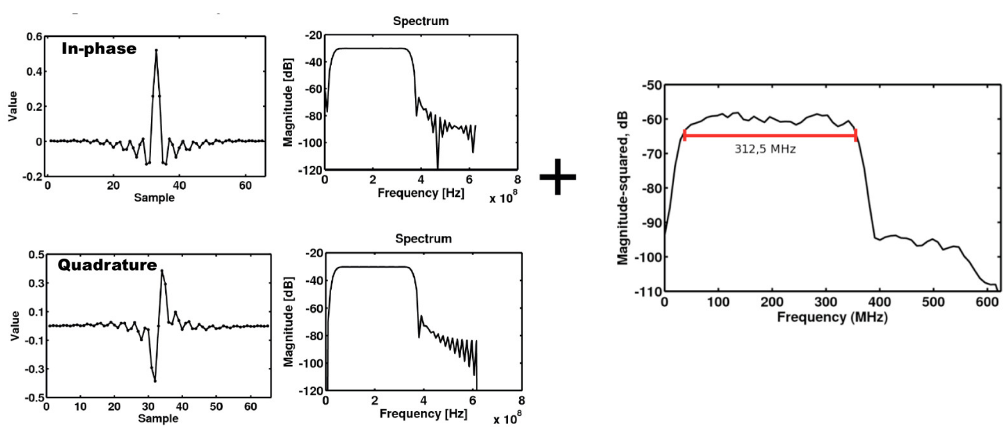

Fig. 2. CAP filters in time and frequency domain, and frequency spectrum of 1.25 Gbps CAP-16 after ArbWG

The received signal filtered with the receiver CAP filters is decomposed in both orthogonal components. Both components can be represented in an I/Q constellation diagram like QAM signals. Figure 3(a) shows the clear constellation diagram of the demodulated electrical B2B signal. Figure 3(b) shows the demodulated optical B2B with −19 dBm received optical power; constellation after electrical-to-optical conversion is still very clear. Figure 3(c) and d show the signals at − 22 dBm received optical power, for B2B and after 26 km configurations, respectively. No constellation degradation is appreciated after transmission compared to B2B, as it is shown also later in the BER curves.

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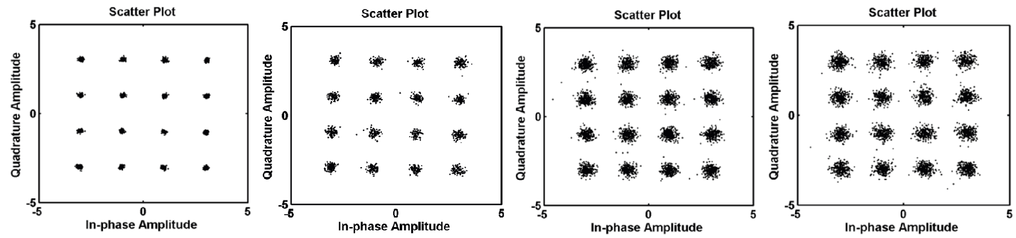

Fig. 3. Constellation CAP-16 for a) electrical B2B, b) optical B2B at -19 dBm, c) optical B2B at -22 dBm. d) after 26 km SSMF at -22 dBm.

Figure 4(a) shows the measured BER curves of the demodulated channel 49 to evaluate the transmission effects and cross talk between channels. The figure compares the performance when only channel 49 is transmitting and when the 4 channels are transmitting simultaneously. No receiver sensitivity power penalty is measured from multiplexing or transmission. Figure 4(b) shows all 4 channels after 26 km transmission. The forward error correction (FEC) limit of BER = $2.2 \bullet 10^{-3}$ is considered as a reference. We achieved receiver power sensitivity below -24 dBm for all the channels.

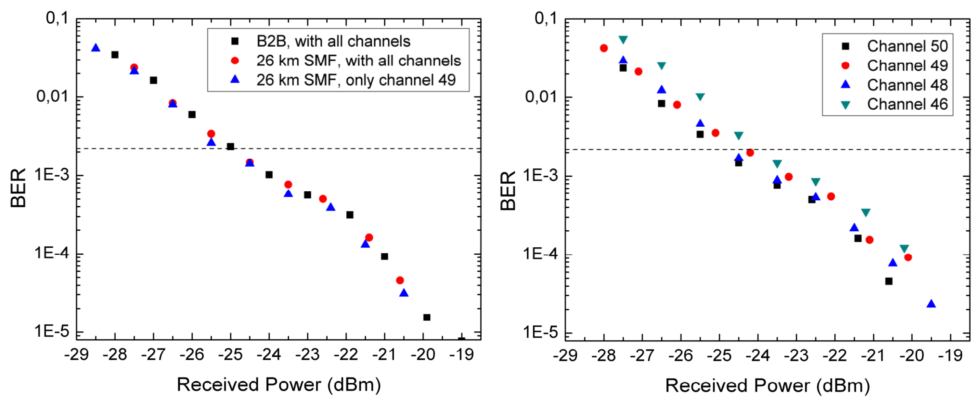

Fig. 4. BER curves CAP-16. a) Channel 49 b) all channels after 26 km SSMF.

5. Simulation of CAP requirements

In this section, simulations have been performed in order to determine the minimum requirements for ADCs and digital filters in a CAP system.

5.1. Resolutions and sample rates:

The price of high performance Analog to Digital Converters (ADC) will not be suitable for PON applications where cost reduction is the main challenge. It is desirable to reduce the requirements in terms of sample rate and vertical resolution of ADCs. Simulations have been performed to analyze what are the requirements for CAP-16 signals with respect to ADC resolution, number of tabs in filters, and degree of oversampling in order to obtain good performance with the minimum complexity. Figure 5 shows the demodulated constellation of the simulated signal when different precision of the filter coefficients is used. The number of filter taps on the simulation was set to the experimental value used of 65.

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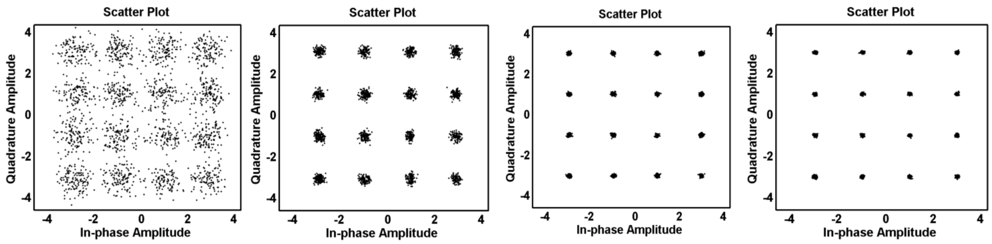

Fig. 5. Constellation CAP-16 for a) 4-bit precision, b) 6-bit precision, c) 8-bit precision, d) 10-bit precision.

Figure 6(a) shows the error vector magnitude (EVM) respect to the coefficient precision. EVM of 12% corresponds to a BER at the FEC limit for a 16 QAM constellation [8] [9], which is the same constellation than CAP-16. Bit precision of 6 or more are needed for electrical signal with EVM below 12%.

The second parameter to consider is the sample rate. The maximum baud rate of our ADC allows will depend on the sample rate of the ADC and the required oversampling of the CAP signal. The optimum upsampling factor for a CAP system is 4, as described in [5].

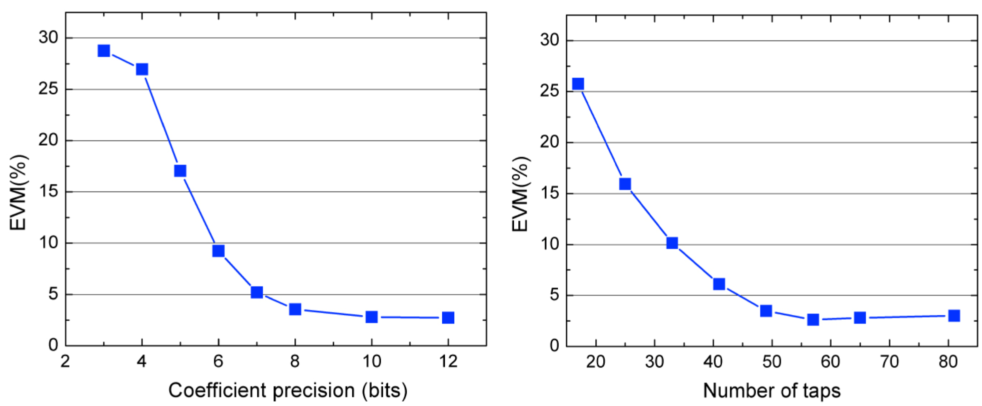

Fig. 6. EVM for CAP 16 respect to a) Coefficient precision, b) number of filter taps

5.2. Filter taps:

CAP modulation has been demonstrated to be simpler than DMT [3]. In contrast with DMT, CAP does not require of IFFT and FFT to generate and demodulate multiple subcarriers. Instead, CAP uses a filter or digital convolution with less computational complexity. This simplicity makes CAP suitable for next generation access networks where cost is the main challenge. The computational complexity to generate and demodulate CAP signals is directly related with the number of taps of the CAP filter. Therefore, it is important to investigate the requirements of the CAP filter in order to decrease the computational complexity maintaining a good performance. Figure 7 shows the demodulated constellation of the simulated signal using different number of filter taps. The number of bit precision on the simulation was set to the experimental value used of 10. Figure 6(b) shows the EVM respect to the number of filter taps. For an EVM below 12%, the number of taps has to be 33 or more.

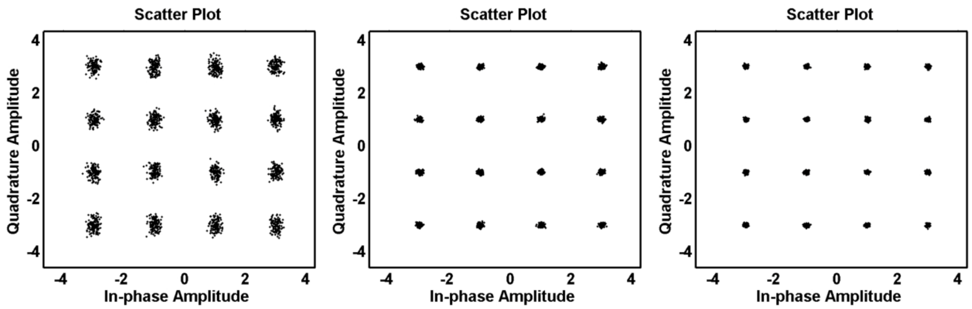

Fig. 7. Constellation CAP-16 for CAP filters with a) 33 taps, b) 49 taps, c) 65 taps

6. Summary

We have experimentally demonstrated directly modulation of CAP-16 in commercially available VCSELs, with a spectral efficiency of 4 bit/s/Hz. The system has been evaluated with 4 close spaced channels at 1.25 Gbps each, for a total bitrate of 5 Gbps over 26 km fiber transmission. All the channels achieved receiver power sensitivity below -24 dBm. Moreover, we have presented simulation on the requirements of CAP signals. Future work will evaluate the system for higher bitrates overcoming the transmitter limitations by using analog CAP filters.

We believe direct CAP modulation of VCSELs is a candidate for next generation PONs and short range systems. CAP allows for scalability in multilevel and multidimension. Therefore, CAP has a potentially very high spectral efficiency attractive for bitrates beyond 15 Gb/s where NRZ-OOK becomes challenging. Due to the high spectral efficiency, it has a low bandwidth occupation and very close channel spacing without crosstalk can be achieved. Therefore is also very attractive solution for dense. WDM-PONs. It has a potentially low cost implementation and simplicity compare to modulation formats with carrier.

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