100 GSa/s BiCMOS Analog Multiplexer Based 100 GBd PAM Transmission over 20 km Single-Mode Fiber in the C-Band

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Abstract *We show application of a novel BiCMOS analog multiplexer for 100 GBd PAM-4, -6 and -8 signal generation. Up to 20 km C-band fiber transmission of optical PAM signals is successfully demonstrated with tunable dispersion compensator and SOA pre-amplified receiver.*

Introduction

Next generation high-speed optical transmission systems targeting bit rates beyond 1 Tbit/s require the generation of high-quality multilevel analog signals at high symbol rates. Today's optical transponders are based on digital-to-analog converters (DAC) and analog-to-digital converters (ADC) manufactured in CMOS technology, which is unlikely to fulfil future requirements on resolution, analog bandwidth and sampling rate. At the transmitter side, an extension of the analog bandwidths can be achieved using analog multiplexers[1-6] (AMUX), which take parallel data paths at lower speeds and interleaves them to form high-speed signals.

Up to now, most of the demonstrated AMUXs are based on InP enabling a large bandwidth of up to 110 GHz at 180 GSa/s[1]. It has been shown that integration of an AMUX with driver amplifier[1] or a hybrid integration of AMUX and modulator[2] can limit the number of electrical high-speed interfaces. Net data rates of 400 Gbit/s using PS-PAM[2] and 300 Gbit/s using discrete multitone[3] were reported in optical transmission experiments. However, InP does not allow for monolithic integration with CMOS based transmitter digital signal processing (DSP) part and DAC, which raises challenges in commercial applications.

An alternative technology is BiCMOS which allows dense integration of high-speed Bipolar transistors and CMOS for lower speed circuitry. Further co-integration with Silicon modulators might also be possible in the future.
SiGe based AMUXs have only been reported with measured electrical PAM-4 eye diagrams at 56 GBd [4] and 100 GBd[5].

In this paper, we demonstrate the first optical 100 GBd PAM transmission using a BiCMOS AMUX in an intensity modulated direct detection (IM-DD) system, achieving line rates of 200 Gbit/s, 250 Gbit/s and 300 Gbit/s using 4, 6 and 8 signal amplitude levels. The PAM signals are generated by a 2:1 AMUX operated at 100 GSa/s.

120 GSa/s 2:1 AMUX

The 2:1 AMUX, first reported in[6], is a prototype designed by Saarland University and works up to 120 GSa/s. It was fabricated in 55 nm BiCMOS technology by STMicroelectronic (f_T=325 GHz, f_{max}=375 GHz). The 1350 µm x 1080 µm AMUX is mounted via wire bonds on an RF-PCB, as depicted in Fig. 1a). The assembled module, depicted in Fig. 1b), consumes about 2.2 W, i.e. 380 mA from a single supply voltage of -5.7 V. The chip and the RF-PCB in Fig. 1a) are designed symmetrically with differential signal inputs on opposite sides of the chip for better multiplexing linearity. This configuration minimizes the coupling between wire bonds of the signal inputs (data paths) and the clock signal (clock path).

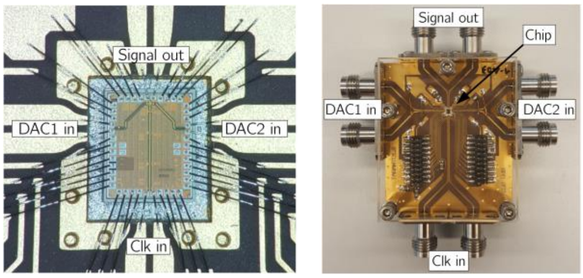

Fig. 1: a) Mounted AMUX chip, b) AMUX module

The AMUX prototype iteratively samples the two input tributaries at up to 120 GSa/s (60 GSa/s on each tributary) at a nominal physical resolution of 8-bits. For tributaries of 30 GHz bandwidth, the AMUX is therefore capable of doubling the bandwidth to 60 GHz. The time-interleaving operation of the AMUX can be modeled, as explained in[6], by a multiplication of one tributary by a binary 10 sequence and the other tributary by a binary 01 sequence.

Fig. 2 shows the effective number of bits (ENoB) of both the AMUX sampling at 100 GSa/s and of the two MICRAM DAC4 modules generating the input signals. The DAC4 modules are operated at 50 GSa/s and have a physical resolution of 6-bit.

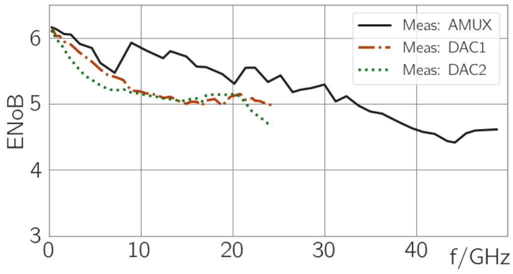

Fig. 2: ENoB comparison of AMUX and DAC4

The AMUX has an ENoB of 6.1 bit at low frequencies, decreasing to 4.4 bit at 44 GHz. In the frequency range of 0 to 25 GHz the AMUX shows better linearity compared to the two individual DACs. The time interleaving operation of the AMUX can lead to destructive interference of the higher harmonics of the two DACs signals depending on the amplitudes and the phases of these harmonics. This destructive interference can reduce harmonic distortion of the AMUX output signal compared to the harmonic distortions present in the two DACs signals. Fig. 3 shows the electrical eye diagrams of the AMUX at 100 GBd and 100 GSa/s.

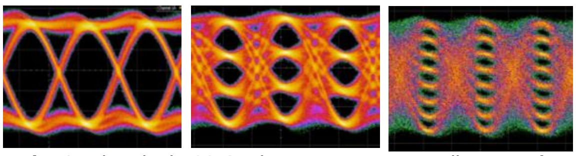

Fig. 3: Electrical 100 GBd AMUX output eye diagrams for OOK, PAM-4 and PAM-8

Experimental Setup

We set up a short-reach IM-DD fiber transmission system with the AMUX in the transmitter to assess the performance of the device for PAM generation. The input signals to the AMUX are from two MICRAM DAC4 devices operating at 100 GSa/s and a symbol rate of 50 GBd, delivering two uncorrelated PAM signals of length 2^{15}. The AMUX combines these into a 100 GBd data stream of length 2^{16}, see Fig. 4 for a schematic of the experimental setup. The two DAC4 and the AMUX share the same 50 GHz clock. The analog data signals from the DACs can be individually shifted in time and adjusted in amplitude at the AMUX input.

At the output of the AMUX, a driver amplifier with 55 GHz of bandwidth is connected to a $LiNbO_3$ Mach-Zehnder modulator (7 dB down at 50 GHz) biased at quadrature modulating an external cavity laser (ECL) emitting at light 1553 nm. The ECL is set to provide 15.5 dBm output power resulting in ~9 dBm transmitter output power, the optical spectrum after modulation is depicted in Fig. 4(i). The transmitter DSP includes mapping of the data and linear digital pre-compensation filters for all transmitter components.

At the receiver a variable attenuator controls the power impinging on the photodiode, having 100 GHz 3-dB bandwidth. To emulate an SOA pre-amplified photodetection, we included an SOA with a noise figure of ~9 dB as a second receiver configuration. The input power into the SOA was varied while the photodiode input power was constant at 7.5 dBm. The electrical signal is digitized by a real-time oscilloscope of 84 GHz bandwidth sampling at 256 GSa/s and captured traces are stored for offline processing. The offline receiver DSP resamples to 2 samples per symbol, optimizes the sampling point, applies decision-directed FIR equalizer updated to minimize the squared error, demodulates symbols to bit and counts bit errors. BERs are always averaged over ~5 million symbols. Regarding performance threshold, we consider three different FEC limits having different coding overheads (OH): KP4 at 5.8% OH, two interleaved extended BCH (1020,988) at 6.69% OH, and a soft decision FEC at 20% OH.

The transmission link consists of standard single mode fiber (SSMF) from 5 to 20 km in 5 km steps. Due to the small dispersion tolerance of 100 GBd signals in C-band IM-DD

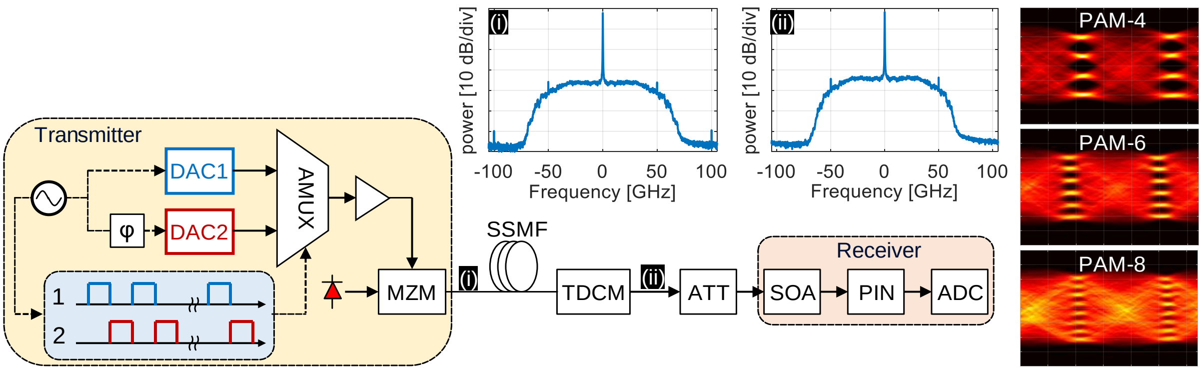

Fig. 4: Schematic of the experimental setup. Insets: Optical spectrum after the modulator (i) and after TDCM (ii), right optical PAM eye diagrams at the modulator output

systems, we applied a tunable dispersion compensator (TDCM). It is based on a Fiber-Bragg grating with ±400 ps tuning range adjustable in steps of 10 ps. The TDCM leads to low pass filtering of the optical signal, down 2 dB at ±50 GHz away from the center frequency, as seen in Fig. 4(ii). The tuning range of the TDCM also limits the possible fiber transmission distance to < 25km.

Results and Discussion

We first assess the performance for PAM-4, -6 and -8 in a back-to-back scenario without optical amplification varying the input power to the photodiode from +7.7 to 0 dBm.

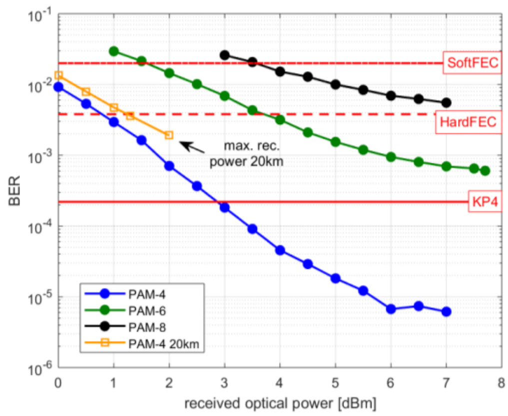

Fig. 6: Back-to-Back BER vs. received power at the photodiode and for PAM-4 after 20 km SSMF transmission

The error floors are in the range of $5{\cdot}10^{-6}$ for PAM-4, $6{\cdot}10^{-4}$ for PAM-6 and $5.5{\cdot}10^{-3}$ for PAM-8, respectively. Having high transmitter output power, we transmitted the PAM-4 signals over 20 km of SSMF without amplification and added the results to Fig. 6. A BER of $1.9{\cdot}10^{-3}$, below hard FEC threshold, is achieved at the maximum received power of 2 dBm. The number of taps for the adaptive decision-directed FIR equalizer is 33 for PAM-4, however, for PAM-6 and PAM-8 161 taps were needed to properly compensate for electrical reflections in the transmitter.

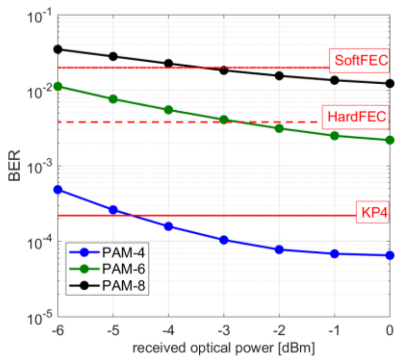

Fig. 7: Back-to-Back BER vs. received power into the SOA

We repeat the back-to-back experiment including an SOA in front of the photodiode. Results are shown in Fig. 7. Compared to the unamplified case the SNR is reduced from 21 dB to 19 dB and the error floor clearly increases for each format due to the 9-dB noise figure of the SOA, but the power budget increases by ~6 dB.

We transmit the PAM signals over 5 to 20km of SSMF, and the results are shown in Fig. 8. In Fig. 8 left all the achieved BERs are below the respective FEC limits for all transmission distances. After 20km SSMF transmission BERs amount to $1.8{\cdot}10^{-4}$ for PAM-4, $3.5{\cdot}10^{-3}$ for PAM-6 and $1.7{\cdot}10^{-2}$ for PAM-8, respectively.

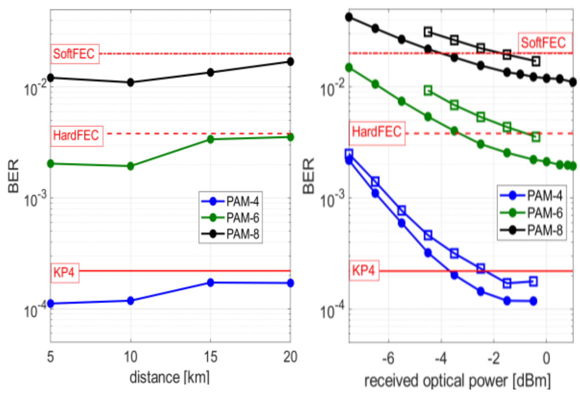

Fig. 8: left: BER vs. transmission distance, right: BER vs. received power for 10km (circles) and 20km (squares)

Removing the required FEC overhead, the resulting net data rates after 20 km transmission amount 189 Gbit/s for PAM-4, 234 Gbit/s for PAM-6 and 250 Gbit/s for PAM-8, respectively.

Conclusions

We demonstrated a 2:1 SiGe AMUX serving an IM-DD optical transmission system at 100 GBd combining two 50 GBd tributaries. When using PAM-4 modulation, transmission in the C-band over 20 km of SSMF followed by a TDCM at BERs below $3.8{\cdot}10^{-3}$ was demonstrated without any optical amplification. The use of an SOA prior to photodetection after 20 km improves the PAM-4 BERs to $1.8{\cdot}10^{-4}$ and enables transmission at BERs below FEC thresholds for hard decision FEC at 6.69% OH for PAM-6 and soft decision FEC at 20% OH for PAM-8. After 20 km fiber transmission we achieved net data rates of 189 Gbit/s for PAM-4, 233 Gbit/s for PAM-6 and 250 Gbit/s for PAM-8 modulation.

Acknowledgements

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