220 GBaud Signal Generation Enabled by a Two-channel 256 GSa/s Arbitrary Waveform Generator and Advanced DSP

Fabio Pittalà(1), Maximilian Schaedler(1), Ginni Khanna(1), Stefano Calabrò(1), Maxim Kuschnerov(1), Changsong Xie(1), Zhicheng Ye(1), Qibing Wang(2), Bofang Zheng(2)

1: Munich Research Center, Huawei Technologies Duesseldorf GmbH, Riesstrasse 25, D-80992, Munich, Germany, fabio.pittala@huawei.com,
2: B&P Laboratory, Huawei Technologies Co. Ltd., Shenzhen 518129, China.

Abstract *We report, to the best of our knowledge, the highest symbol rate of 220 GBaud in optical back-to-back QPSK transmission enabled by a new 256 GSa/s SiGe arbitrary waveform generator, a >50 GHz 6 dB bandwidth GaAs IQ modulator and advanced nonlinear DSP.*

Introduction

Increasing symbol rate is one of the most important dimensions to explore in order to achieve a large-capacity serial transmission system with digital coherent technology. The high-speed digital-to-analog converter (DAC) is the key device to generate a high symbol rate signal beyond 200 GBaud. The sampling rates of DACs have reached 128 GSa/s for technologies based on Silicon-Germanium (SiGe)[1,2] and 120 GSa/s for complementary metal-oxide semi-conductor (CMOS)[3].

Fig. 1 shows recent digital coherent experimental results with symbol rates over 110 GBaud relying on electrical high-speed signal generation techniques. The red dots show data for transmitters using more than one DAC per dimension, while the blue squares show experiments using one DAC per dimension. Using single 128 GSa/s SiGe DACs, symbol rates up to 128 GBaud have been reported[1,2], while the highest reported symbol rate with 120 GSa/s CMOS DACs is 115 GBaud[3]. To realize higher symbol rates, electrical time domain multiplexing (ETDM)[4,5] or bandwidth multi-plexing techniques[6-14] are used. The highest symbol rate reported so far is 192 GBaud and has been obtained for the single-carrier QPSK format using bandwidth multiplexing supported by digital pre-processing and an integrated electro-optical

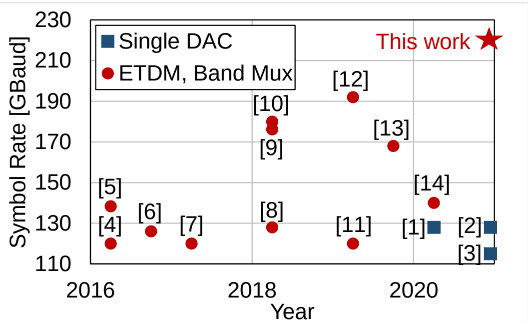

Fig. 1: Recent ≥110 GBaud coherent experiments using IQ modulator: symbol rate growth per year.

front-end[12]. Solutions based on multi-DACs per-dimension demonstrate that high bit rates can indeed be achieved by pushing up symbol rates, at the expense of a reduced signal integrity.

In this preliminary study, we have successfully generated the record symbol rate of 220 GBaud for QPSK signalling by using a 256 GSa/s arbitrary wavelength generator (AWG)[15], a >50 GHz 6 dB bandwidth gallium arsenide (GaAs) IQ modulator [16] and advanced nonlinear digital signal-processing (DSP) [17,18].

128/256 GSa/s AWG and its Features

A new SiGe DAC application-specific integrated circuit (DAC-ASIC) that translates the memory data into an analog signal is used in a 128/256 GSa/s arbitrary waveform generator (AWG) recently launched into the market[15]. It uses a novel type of package for the DAC-ASIC which avoids soldering sensitive radio frequency (RF) parts by placing an RF connector at the DAC-ASIC, thus avoiding signal degradation. A built-in amplifier delivers high speed and quality output signals with a smooth frequency roll-off. The AWG can support up to four synchronized channels operating simultaneously in one module, featuring continuous sample rate ranging from 100 to 128 GSa/s and from 200 to 256 GSa/s. The main specifications of the AWG are 65 GHz nominal analog bandwidth, up to 6 bits ENOB, intrinsic jitter < 60 fs, 1.4 V_{pp} differential output voltage at 128 GBaud, channel-to-channel skew adjustment with 15 fs resolution, < 150 dBc wideband phase noise for frequencies > 1 MHz. To double the sampling rate from 128 to 256 GSa/s, a time interleaver that consists of a total of four power combiners (considering differential operation) is connected to two DAC-ASICs. For mechanical stability, the power combiners are mounted in a metal housing making the setup mechanically stable and avoiding phase-induced instabilities of the signal. Due to the insertion loss of the power combiners,

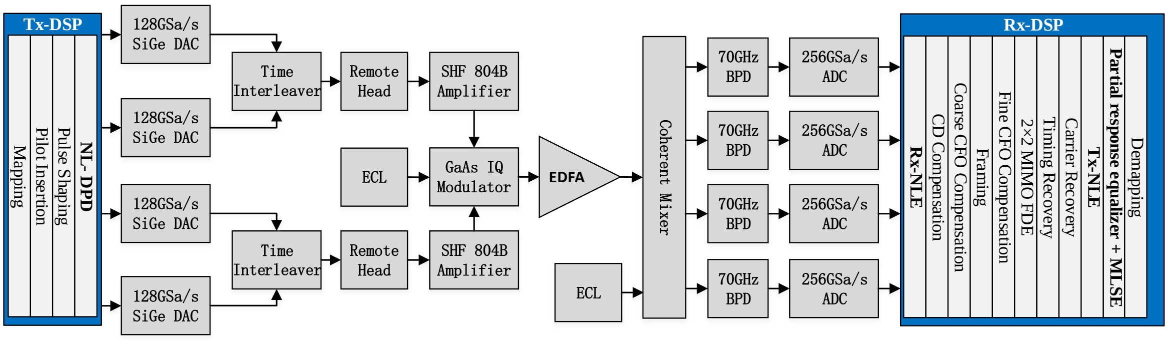

Fig. 2: Schematic of the experimental setup.

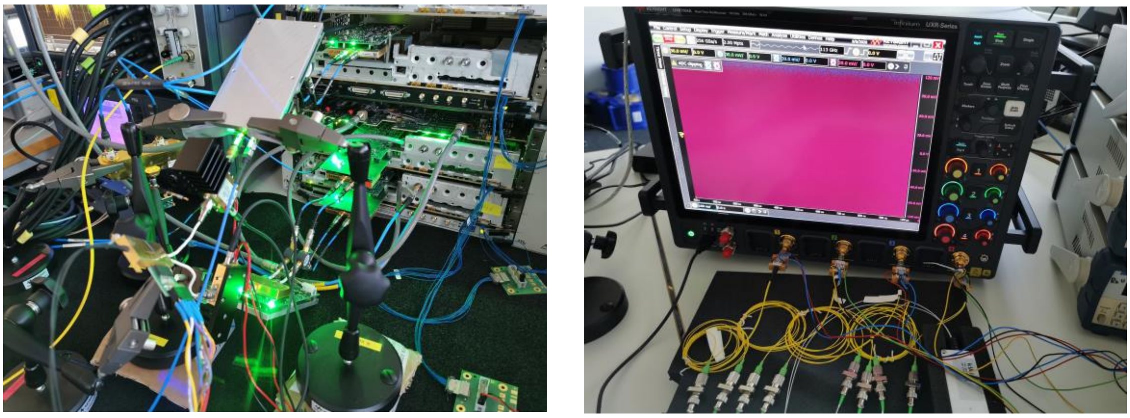

Fig. 3: Pictures of the experimental setup: transmitter (left), receiver (right).

external RF amplifiers – named "remote heads" by the AWG supplier – are required.

Experimental Setup

The system setup is shown in Fig. 2. The data signal of each real component is generated by two 128 GSa/s time-interleaved SiGe DAC-ASICs to get 256 GSa/s output sampling rate. The RF outputs are then connected to the remote heads to compensate the loss of the interleaver. The RF amplitude of a single channel after the remote head for symbol rates exceeding 200 GBaud is below 200 mV_{pp}. Therefore, two SHF 804B amplifiers with 60 GHz 3 dB bandwidth and 22 dB gain are used to drive an electro-optic IQ modulator based on GaAs guided-wave technology. As shown in Fig. 4-right, the 6 dB bandwidth of this modulator exceeds 50 GHz. In Fig. 3-left it can be observed that due to the mechanical arrangement of this transmitter the RF connections are about 20 cm long. In addition, it should be noted that all RF connectors (1.85mm) and RF cables in the setup are designed to work up to 67 GHz. The measured frequency response of the electrical part of the transmitter is shown in Fig. 4-left. The IQ modulator is fed by a <100 kHz linewidth external cavity laser (ECL) with 16 dBm output power at 1550 nm. The receiver consists of a coherent mixer, four balanced 70 GHz photodetectors connected to a 256 GSa/s 110 GHz UXR oscilloscope, Fig. 3-right. Another <100 kHz ECL with 16 dBm output power at 1550 nm is used as local oscillator. The optical power of the input signal into the coherent mixer is set to 4 dBm.

The DSP makes use of advanced and fully adaptive nonlinear component equalizers, targeting imperfections such as bandwidth limitations, frequency dependent I/Q imbalance and skew, phase ripple, I/Q crosstalk and high-order nonlinearities at transmitter and receiver. Digital pre-distortion (DPD) is used to compensate the imperfections of the transmitter components, i.e. DAC, driver and modulator. At the receiver, a first digital Volterra equalizer (Rx-NLE in Fig. 2) addresses the imperfections of the receiver components, i.e. optical-electronic front-end and analog-to-digital converter (ADC). After channel equalization and demodulation (including carrier phase recovery), another Volterra equalizer (Tx-NLE in Fig. 2) compensates for the residual imperfections of the transmitter.

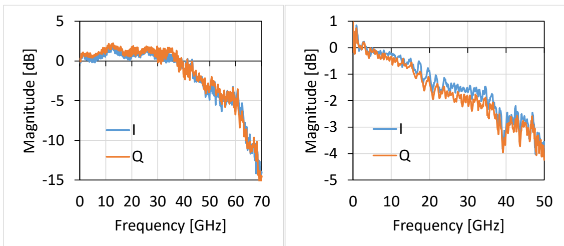

Fig. 4: Measured frequency response for concatenation of 256 GSa/s AWG, remote head and SHF 804B amplifier (left), GaAs IQ modulator (right).

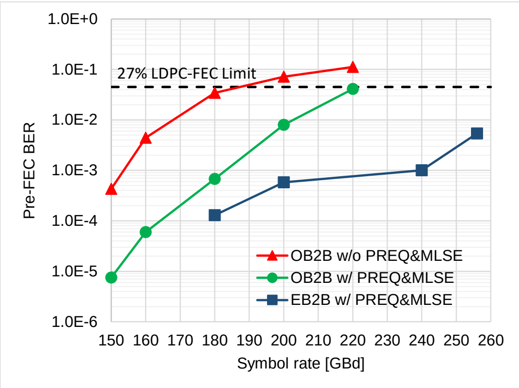

Fig. 5: Experimental results: pre-FEC BER versus symbol rate for electrical and optical B2B.

Since the transponder imperfections arise mostly in the electrical domain, where the two tributaries are independently processed, also the equalizers operate on the real tributaries rather than on the complex baseband signal. Finally, partial-response equalization (PREQ) with impulse response 1+αD is implemented to whiten the noise, followed by two real-valued maximum likelihood sequence estimators (MLSEs) with one memory tap used for sequence detection[17,18].

Experimental Results

The experimental results, in terms of pre- forward error correction (FEC) bit-error-ratio (BER) versus symbol rate, are shown in Fig. 5. In addition to optical back-to-back (B2B) results we report also the electrical measurements for reference. In this case, the outputs of the remote heads are connected directly to the inputs of the UXR oscilloscope. Using the QPSK format and without transmitter DSP we could transmit up to the highest achievable symbol rate of 256 GBaud with a pre-FEC BER of 5.4e-3.

In optical B2B configuration, the transmitter DSP performs a root-raised cosine (RRC) spectral shaping with roll-off factor of 0.2 and pre-equalization of the electro-optical front-end, while at the receiver DSP, the Rx-NLE is set to have 360 linear taps and 7 taps of the 2nd and 4th order, and the Tx-NLE is set to have 450 linear taps and 1 tap of the 2nd order. The large number of linear taps in the equalizers is chosen to cope with reflections in the setup assembly and avoid fine optimization, however it could be reduced with negligible impact on performance in an integrated device. The larger nonlinear contribution of the Rx-NLE is due to the high optical power of the signal and local oscillator lasers leading to nonlinear behaviour of the photodetectors. The parameter α of the impulse response of the PREQ is set to 0.7 for symbol rates equal to 150 and 160 GBaud, and is increased to 1 for higher symbol rates. The received digital spectrum for 160 and 220 GBaud signal is depicted in Fig. 6-

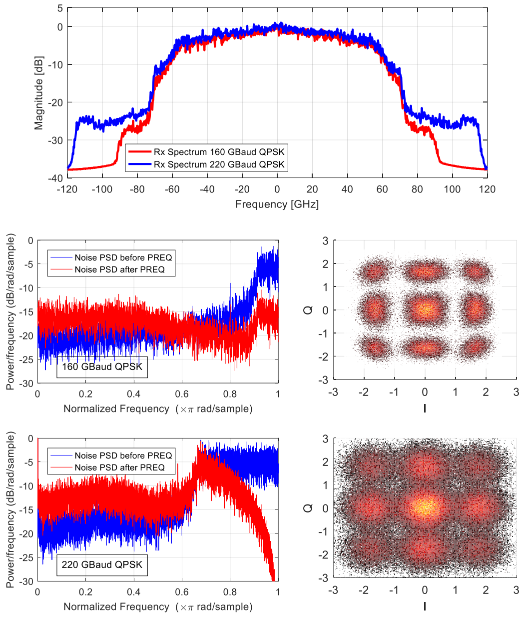

Fig. 6: Digital received spectrum for 160 and 200 GBaud signals (top), noise PSD before and after the whitening filter with constellation plot after the whitening filter for 160 (middle) and 220 GBaud signals (bottom), respectively.

top. In both cases, it can be observed a severe bandwidth limitation with attenuation >20 dB starting from 73 GHz. The noise power spectral density (PSD) before (blue) and after (red) the whitening filter for 160 and 220 GBaud signals is illustrated in Fig. 5-middle and Fig. 5-bottom, respectively. The constellations obtained after the PREQ are also included. Note that the partial-response filter introduces inter-symbol inter-ference (ISI), which is subsequently tackled by the MLSE.

As shown in Fig. 5 we achieved up to 220 GBaud QPSK signal transmission with pre-FEC BER of 4.1e-2. Assuming a 27% low density parity check (LDPC) code[19,20] with BER threshold of 4.5e-2 this corresponds to 346.46 Gbit/s net bitrate per polarization.

Conclusions

In a preliminary investigation, we demonstrated feasibility of beyond 200 GBaud signal generation. In optical back-to-back configuration we transmitted 220 GBaud QPSK signal using a 256 GSa/s arbitrary waveform generation with 65 GHz 3 dB bandwidth and a >50 GHz 6 dB bandwidth GaAs IQ modulator, powered by advanced DSP to compensate for bandwidth limitations and nonlinearities of the setup. To the best of our knowledge this is the highest symbol rate achieved so far with an increase of about 15% with respect to previous published record.

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