High-speed discrete multitone serial data transmission over multi-mode fibre at gross data rates up to 224 Gbit/s achieved with directly modulated oxide-confined vertical cavity surface emitting lasers at 850 and 910 nm are presented.

Introduction: The directly modulated vertical cavity surface emitting lasers (VCSELs) in combination with the multimode fibre (MMF) are widely used in data centre applications at distances up to 300 m, due to high data rate, low-energy consumption and low cost. The recent 100 Gbit/s industrial standards consider the use of 4-PAM modulation at 50 Gb/s [1]. Recently, optical internetworking forum launched a development project targeting serial 224 Gbps electrical interfaces (CEI-224G) [1] and the IEEE 802.3 New Ethernet Applications group initiated a call for interest targeting 200 Gbit/s per lane for electrical and optical interconnects [2]. In both cases, the modulation formats that will be utilised are yet to be selected.

So far 168 Gbit/s could be achieved with 4-PAM modulation by applying root-raised-cosine pre-emphasis and equalisation [3]. However, bandwidth and signal-to-noise ratio (SNR) requirements may limit applicability of this modulation format to achieve even higher data rates. Therefore, alternative modulation formats are being explored for the next-generation short-range links with data rates above 100 Gbit/s. Among those are quadrature amplitude modulation (QAM) at 140 Gbit/s [4] and discrete multi-tone (DMT) at 160 Gbit/s [5].

In DMT Modulation, the signal is divided into discrete subcarriers, where each of the subcarriers is modulated with QAM. The QAM level of the subcarrier is determined through the SNR value at its frequency. Performance can be further enhanced by application of the soft-decision forward error correction (SD-FEC) instead of hard-decision (HD). SD-FEC operates at BER limit of 2.7e-2 [6] while HD-FEC requires BER below 4e-3 [7]. However, SD-FEC comes at the price of higher energy consumption and latency. Further increase of the system bandwidth can be realised by pre-emphasis of the higher frequency components at the transmitter, however it is limited by the available dynamic range of the DAC and the system noise [5].

In [5] we have reported 10 m MMF transmission with DMT at 135 Gbit/s with HD-FEC and 161 Gbit/s with SD-FEC achieved with ~20 GHz 850 nm VCSELs. In this paper, utilising the next-generation 850 nm and 910 nm VCSELs we demonstrate DMT transmission up a gross data rate of 224 Gbit/s.

VCSEL Technology: As stated above, the 850 and 910 nm oxide-confined VCSELs with an anti-wave-guiding AlAs-rich core with apertures ranging from 3 to 5 µm [8] were used in the experiments. Through optimisation of damping and resonance frequency it was possible to achieve ~3 dB bandwidth above 30 GHz.

Figure 1(a,b) shows the power–current–voltage and the spectral characteristics of the investigated lasers. Both VCSELs delivered up to 3 mW optical power and had a ~0.5 mA threshold current. The frequency response of the VCSELs is displayed in Figure 2(a). Both VCSELs have high bandwidth with a smooth roll-off.

Figure 2 presents the 50 Gbit/s NRZ eye-diagrams for both VCSELs measured with 5 mA bias current and a 500 Vpp non-return-to-zero voltage swing. Significant reduction of the bandwidth was observed in the experiments. A 30 GHz receiver (MatrIQ-O2E 1201-1-FA) and a linear amplifier (SHF 804 TL, 55 GHz) were used at the receiver side of the setup. A realtime oscilloscope with 256 GSa/s and 110 GHz bandwidth (Keysight Infinium) captured the received signal for the further off-line signal processing.

Experimental Setup: Figure 3 shows the experimental setup. The electrical DMT signals are generated by a 120 GSa/s arbitrary waveform generator (AWG, MB194A Keysight). The VCSELs were contact placed on a probing stage using 100 µm pitch RF probes and biased at 5 mA from a DC source through a bias-T. The optical signal is coupled into the MMF (OM4, 10 m) using a lensed fibre coupling unit. The OM4 fibre used in the setup was not optimised for 910 nm signals, although no significant reduction of the bandwidth was observed in the experiments. A 30 GHz receiver (MatriQ-O2E 1201-1-FA) and a linear amplifier (SHF 804 TL, 55 GHz) were used at the receiver side of the setup. A real-time oscilloscope with 256 GSa/s and 110 GHz bandwidth (Keysight Infinium) captured the received signal for the further off-line signal processing.

Figure 4(b) shows the frequency response of the system that includes the AWG-OSC pair, amplifiers and electrical cabling (electrical reference). The optical transmission system response is also presented for both AWG and VCSEL types. The 12-dB modulation bandwidth for the transmission system was 30 GHz with a smooth roll-off of 1.5 dB/GHz up to about 40 GHz. The transmission system frequency response was limited by the combined VCSEL (Figure 2(b)) and photo receiver characteristics.
The OM4 wideband fibre has high modal bandwidth and small attenuation both for 850 and 910 nm signals. Due to the narrow spectral width of the VCSELs studied, the chromatic dispersion can also be significantly reduced. Therefore, we do not expect fibre lengths up to 300 m to significantly limit the transmission, as demonstrated in ref. [5].

The digital signal processing at the transmitter side included: bit-stream generation, serial to parallel conversion, bit mapping, addition of training symbols for channel estimation, inverse fast Fourier transformation (IFFT, length 512, Hermitian symmetry), cyclic prefix (CP) insertion (16 samples) and parallel to serial conversion followed by up-sampling to the DAC sampling rate. Further samples assisted the synchronisation. Finally, the transmitted signal was clipped in the digital domain to limit the peak-to-average power ratio (PAPR) and enabled a constant signal power after the DAC. The clipping ratio was set to limit the PAPR to ~10 dB. A 4-QAM modulated training sequence enabled SNR measurements for the bit loading on the each DMT subcarrier. Bit per symbol value determines the level of the QAM at a specific subcarrier used. Optimum bit loading was based on the known SNR values and aimed at achieving a given target BER target on all subcarriers. Power loading was optional to redistribute power among the subcarriers and matching the available SNR to the switching thresholds.

The receiver signal processing included signal down-sampling, low-pass filtering, synchronisation, serial to parallel conversion, CP removal, FFT, a single-tap equaliser for each subcarrier, parallel to serial conversion, the BER/EVM (Error Vector Magnitude) estimation and bit loading.

The use of pre-emphasis to compensate for the channel, as used in ref. [5], did not show any improvements and was not considered. Note that a FEC was not implemented.

**Results:** Figure 5(a) shows the signal-to-noise ratio (SNR) for >170 Gbit/s generated signals, for the electrical reference system and for both VCSELs. The SNR was derived from the measured error vector magnitude of each subcarrier. Close to DC a drop in SNR compared to the electrical case can be observed, which is caused by unwanted reflections between the coupling fibre and the VCSEL since no special anti-reflection coated components were used in this test setup. The drop at higher frequencies can be attributed to the system frequency response, as it can be also observed in the electrical SNR measurement.

Figure 5(b) shows the bit-loading, total gross data rate and average BER at different target BERs for the 850 nm VCSEL. Figure 6 shows the BER measurement for each sub-carrier for the 850 nm link for the signals generated for the 133 and 224 Gbit/s cases. 910 nm data differs only slightly due to a similar bandwidth and SNR profiles. It can be observed that modulation frequencies up to 40 GHz are actually used with up 128 QAM at the lower subcarriers. The reduced loading of bits at higher frequencies can be attributed to the frequency response of the optical link. It follows from these results, that the DMT signal with a bandwidth far beyond the 3 dB bandwidth of the transmission system, suffers significantly due to the high attenuation at the higher frequencies, as expected. Low frequency noise that presumably comes from the optical back reflections is another factor that seems to reduce the SNR and limit the signal quality.

To further evaluate the performance of the link, the maximum achievable gross data rate for different target BERs was measured. Figure 7 shows the results for both VCSEL types. A polynomial interpolation connects the measured values what allows estimating the data rate at the commonly assumed BER which can be corrected by SD and HD FECs. Gross data rates of ~180 Gbit/s are feasible using HD-FEC and rates up to 224 Gbit/s are achievable based on SD-FEC limit.

**Conclusion:** A new generation of ~30 GHz VCSELs has been introduced, which enables higher data rates and show a potential in emerging standards for 224 Gbit/s per lane data transmission. Data transmission with BER below SD-FEC limit up to 224 Gbit/s for 850 nm and 219 Gbit/s for 910 nm VCSELs was demonstrated. At the HD-FEC limit, 180 Gbit/s are achievable at both wavelengths.

Although the bandwidth is sufficient, the link suffers strongly from noise caused limitations both at low and high frequencies that have to be addressed in the future.

The presented results proof that the next generation VCSEL-based MMF links can support the upcoming 224 Gbit/s applications.

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Received: 10 December 2020 doi: 10.1049/el.2021.3026

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