37 Gbps Transmission Over 200 m of MMF Using Single Cycle Subcarrier Modulation and a VCSEL with 20 GHz Modulation Bandwidth

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Abstract *We report transmission at 37.2 Gb/s over 200 m of multimode fibre using a directly modulated VCSEL operating at 850 nm, using 20 GHz modulation bandwidth.*

Introduction

In recent years, there has been a significant interest in the short range optical links. In this type of links multimode fibers are preferred, because they allow larger alignment tolerances in the transceiver components and connectors. Low cost vertical cavity surface emitting lasers (VCSELs) are often proposed for such systems. Recently, high speed VCSELs operating at 850 nm wavelength, have been developed[1,2]. VCSELs capable of supporting 40 Gbps On-Off Keying (OOK) modulation were demonstrated, but only back-to back eye diagrams were reported[2]. Modal dispersion in multimode fibers presents a significant challenge to transmission with OOK over longer distances at such high bitrate, therefore more sophisticated modulation formats have to be used to deal with the dispersion. While promising results in terms of spectral efficiency and dispersion mitigation have been demonstrated using discrete multi-tone modulation (DMT)[3,4], achievable symbol rates are limited by the speed of the fastest available state of the art analogue to digital (ADC) and digital to analogue (DAC) converters. Analogue bandwidth of DACs is still lower than modern VCSELs, so the potential of those lasers cannot be fully exploited. Moreover DMT, as a sub-class of orthogonal frequency division multiplexing (OFDM) has disadvantages like high peak-to-average power ratio (PAPR)[5] and high processing power requirements which hinder real time implementations. All multiple subcarrier systems have the disadvantage of low power efficiency[6].

In this paper we report transmission of 37.2 Gbps over 200 m of multimode fibre using 16 QAM on a single subcarrier in 20 GHz modulation bandwidth. The VCSEL used was reported in earlier publication[1]. In order to realize a real-time subcarrier transmitter, we employ the principle of single cycle subcarrier modulation[7] which has already been applied in single-mode systems[8,9]. The main advantage of this method is that the broadband multi-level QAM transmitters can be readily implemented using existing hardware and the bandwidth of the DAC is no longer a limitation. This technique is based on digital logic gates to generate the QAM signal and removes the need for digital signal processing (DSP) and a DAC from the transmitter. The receiver is, however, using offline DSP, because of the added benefit of equalization. Practical DSP receivers with equalizers have been demostrated by Nortel and CoreOptics.

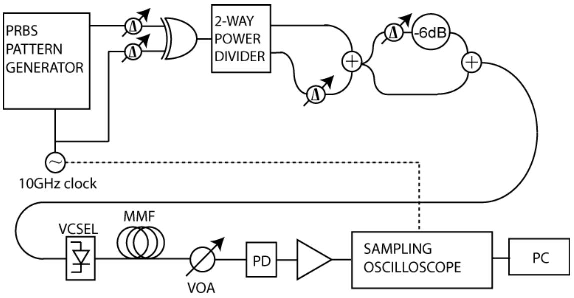

Fig. 1: Test setup structure, including the 16-QAM since cycle subcarrier modulator

Test setup

The test setup is illustrated in Fig. 1. The transmitter end of the test system consists of a real time 16-QAM single cycle sub-carrier modulator and VCSEL with a 20 GHz modulation bandwidth. We use a single sub-carrier at a frequency of 10 GHz, and symbol rate of 10 Gbaud. The modulation format is 16-QAM, yielding 4 bits per symbol and a bit rate of 40 Gbps, which includes 7% overhead for the Forward Error Correction (FEC) yielding 37.2 Gbps usable throughput. The modu-

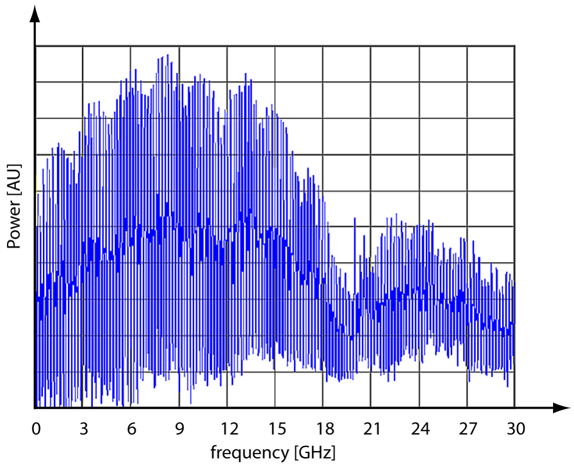

Fig. 2: Electrical spectrum of the generated subcarrier signal.

lated sub-carrier was generated using digital XOR gates[8]. A clock signal at 10 GHz is applied to one input of a single XOR gate, fulfilling the role of the RF carrier. The second input is supplied with binary data at 10 Gbps, to produce a BPSK signal by inverting, or not inverting the RF carrier. A QPSK signal is generated by combining outputs of two gates, delayed in phase by 90°. Combining a QPSK signal from another two gates, in phase and attenuated by 6 dB generates 16-QAM signal. To reduce the number of gates used, we combined decorrelated outputs of a single gate. This method of emulation does not affect the BER results or signal properties. The electrical spectrum of the generated signal is shown in Fig. 2. It is clear from this figure that the occupied bandwidth extends from 0 to 20 GHz. A sidelobe in frequency range above 20 GHz is also present in Fig. 2. The generted electrical signal, with added bias, was fed to the VCSEL mentioned previously[1].The amount of power in the sidelobe could be controlled by use of pulse shaping, but the sidelobe was suppressed anyway because it extended beyond the available bandwidth. The VCSEL was coupled to the MMF via a lens system. Transmission lengths of 100 m, 200 m and 300 m of MMF as well as a back to back (BTB) configuration using a short patch cord were used. The fibre was OM3+ standard fibre, manufactured by Draka, with a bandwidth-distance product of 4700 MHz km. To vary the optical power level at the receiver, a varaible optical attenuator (VOA) was used. The receiver side consisted of a photodetector (New Focus 1481-S-50), which has 3 dB electrical bandwidth of 25 GHz, followed by broadband amplifier (SHF 105AP) and a LeCroy

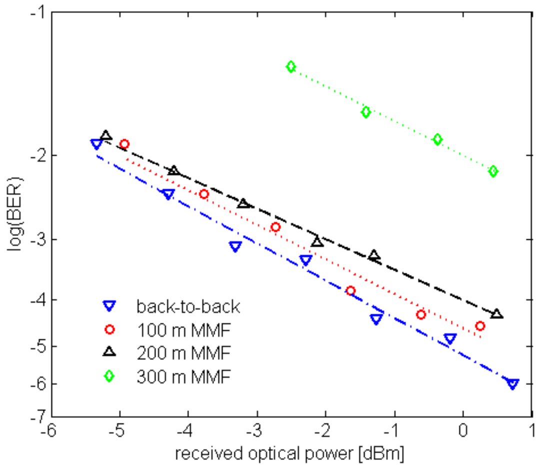

Fig. 3: BER vs received optical power for back to back, 100 m, 200 m and 300 m of multimode fibre.

WaveExpert 100H sampling oscilloscope with 50 GHz sampling head. The demodulation and error calculation was implemented off-line on a personal computer. Decision directed adaptive LMS equalizer with 9 taps was used in the off-line receiver. BER values lower than 10^{-6} could not be obtained within a short processing time, therefore use of an FEC with conservative 7% overhead is assumed, lowering the usable bit-rate. Should a production ready solution be devised, the error correction could be added to the DSP chip, to make the overall system more compact. The DSP is already needed for the 16-QAM signal recovery.

Experimental results

BER results are taken for the three mentioned transmission distances and a BTB case. The maximum reach for transmission in our system is 200 m. Lowest achieved BER for a BTB configuration was 10^{-6} at power level of 0.7 dBm.

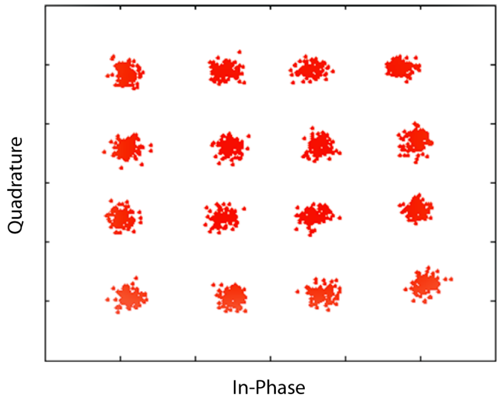

Fig. 4: 16-QAM, 10 Gbaud constellation diagram after back-to-back transmission after equalization.

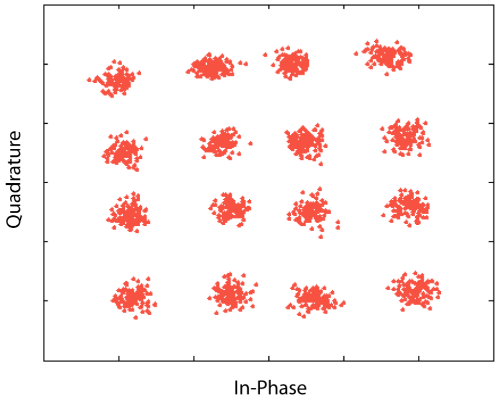

Fig. 5: 16-QAM, 10 Gbaud constellation diagram after transmission over 200 m of multimode fibre, after equalization.

BER lower than $7 \cdot 10^{-3}$ could not be achieved for the 300 m transmission reach and consequently an error free transmission with the assumed FEC overhead is not possible. The plots of the BER versus received optical power are presented in Fig. 3. From the value of the bandwidth-distance product, it follows that at 200 m the available fibre bandwidth is about 23.5 GHz, while at 300 m it is about 15.6 GHz. The transmitted signal had 20 GHz bandwidth and while an equalizer was used in the off-line receiver, an equalizer cannot work effectively outside the channel bandwidth, which is reflected in the degradation of BER results after transmission over 300 m of MMF. Constellation diagrams retrieved for the BTB configuration and after transmission over 200 m and 300 m, are presented in Figs. 4-6. All figures present the constellation diagrams after equalization. For the evaluation of the constellation diagrams the optical attenuator was removed and the received optical power was close to 3dBm. The signal after 200 m of MMF was very good, compared to the BTB case. Constellation diagram evaluated after transmission over 300 m of MMF indicates severe degradation. The BER results for the level of received optical power, for which the constellation diagrams were evaluated, are not included in Fig. 3, because the BER was too low to be reliably measured. For a 300 m the BER would be measurable, but it could not be compared with shorter distances at the same power level.

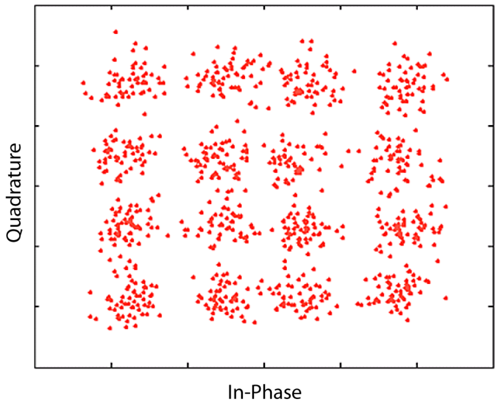

Fig. 6: 16-QAM, 10 Gbaud constellation diagram after transmission over 300 m of multimode fibre, after equalization.

The BER results could be better, if at the time of the experiment photoreceivers with integrated low nosie transimpedance amplifiers (TIAs), operating at 850 nm, with sufficient electrical bandwidth were available.

Conclusions

We have demonstrated that it is possible to exploit wide modulation bandwidth of modern VCSELs, using 16-QAM modulation format on a single subcarrier, without use of expensive DACs in the transmitter end. The transmitter was working in real time, while receiver was implemented off-line. Transmission of 37.2 Gbps in 20 GHz modulation bandwidth over 200 m of MMF was achieved. The system performance is partially limited by the thermal noise in the receiver and BER results can be further improved if low noise integrated photo-receivers operating at 850 nm with sufficient bandwidth will be developed.

Acknowledgements

This work was supported by the Swedish Foundation for Strategic Research (SSF) and the European FP7 project VISIT.

References

1 P. Westbergh et al. *Electronics Letters*, 45(7):366–368, 2009.
2 S. Blokhin et al. *Electronics Letters*, 45(10):501–503, 7 2009.
3 H. Yang et al. *Journal of Lightwave Technology*, 28(4):352–359, 2010.
4 H. Yang et al. OFC'10, OWA4 (2010).
5 J. Proakis. *Digital Communications*. McGraw-Hill, 5th edition.
6 S. Teramoto et al. *IEEE Transactions on Communications*, 53(10):1738–1743, 2005.
7 A. Wiberg et al. OFC'09 OTuE1, (2009).
8 B.-E. Olsson and A. Alping. AOE'08 SaF3, (2008).
9 B.-E. Olsson et al. OFC'10 OMK5, (2010).