49 Gbit/s Direct-Modulation and Direct-Detection Transmission over 80 km SMF-28 without Optical Amplification or Filtering

Zhixin Liu(1), M. Sezer Erkılınç(2), Brian Kelly(3), John O'Carroll(3), Richard Phelan(3),
Benn C. Thomsen(2), Robert I. Killey(2), David J. Richardson(1), Polina Bayvel(2), and Radan Slavík(1)

(1) Optoelectronics Research Centre, University of Southampton, Southampton, U.K. z.liu@soton.ac.uk
(2) Optical Networks Group, Dept. of Electronic & Electrical Engineering, UCL (University College London), London, U.K.
(3) Eblana Photonics, Dublin, Ireland.

Abstract We demonstrate direct-modulation of a discrete mode laser using Discrete Multi-Tone modulation for transmission distances up to 100 km in the 1550 nm band. A large operational temperature range (0-65ºC) is also demonstrated.

Introduction

High-capacity and low-cost transmission over distances of up to 80 km is of interest for inter-data centre communications and short-reach metro networks[1]. Direct-modulation direct-detection (DM-DD) systems using spectrally-efficient modulation formats are becoming increasingly attractive as they offer large transmission capacities with low power consumption, a small form factor, and ultimately a low cost-per-bit[2-4].

Repeater-less high data rate (>28 Gbit/s per channel) transmission over distances beyond 40 km generally requires operating in the low-loss 1550-nm telecom band which is impaired by chromatic dispersion. Its adverse effect can be suppressed by transmitting a single-sideband signal – e.g., in reference 2, a filter based on an optical delay line interferometer (DI) was used to generate vestigial side-band (VSB) signals for 100 km SMF-28 transmission[2]. However, adding such a narrowband optical filter requires the laser wavelength to be locked to the filter to maintain optimal performance, thereby increasing the cost, reducing the potential for tunability, and generally increasing system complexity. The effect of chromatic dispersion could be also mitigated using digital signal processing (DSP). However, this requires correct demodulation of the transmitted signal for interference cancellation, which demands a high signal-to-noise ratio (SNR) and thus far only modest single span transmission distances have been acheived[3]. Recently, the use of the discrete multitone (DMT) format has become widespread as it maximizes the achievable data rates even when subject to limited electronic bandwidth or chromatic dispersion associated frequency fading[4]. To the best of our knowledge, none of these approaches has achieved single-channel data rates beyond 28 Gbit/s for transmission distances over 40 km without in-line or receiver-side optical amplification and optical band pass filtering.

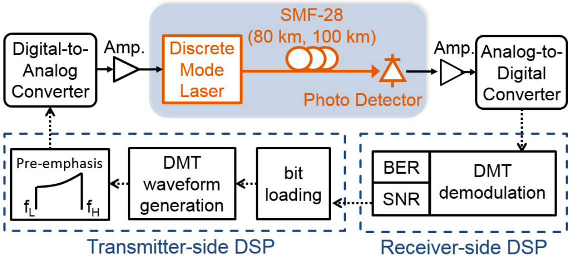

Fig. 1: Experimental setup

In this paper, we first demonstrate 28 Gbit/s DM-DD single-span transmission over 100 km of SMF-28 without the need for either optical amplification or dispersion compensation using moderate-bandwidth (16 GHz) electronics. Following this, we perform a data transmission at 49 Gbit/s over 80-km SMF-28 with the state-of-the-art electronics (92 GS/s sampling rate analogue-to-digital converter and 80 GS/s digital-to-analogue converter). The data throughput was achieved by directly modulating a semiconductor laser (DML) using the DMT format. The DML has a single epigrowth 'discrete mode' structure[5] and is capable of delivering. >28Gbit/s over a large temperature range (0~65°C), promising potential uncooled operation. As our system uses minimum optical hardware (i.e., an uncooled directly-modulated laser on the transmitter side and a single-ended photodiode at the receiver side), it has potential to become both a low-cost and compact solution.

Experimental setup

The experimental setup is shown in Fig.1. The DML emits at 1548 nm at room temperature (20°C). It has a cavity length of 275 µm and a 3-dB modulation bandwidth of 16 GHz[5]. The laser used in the experiment was butterfly-packaged with a Thermo-Electric Cooler (TEC, used to heat or cool the laser over the 0-65°C temperature

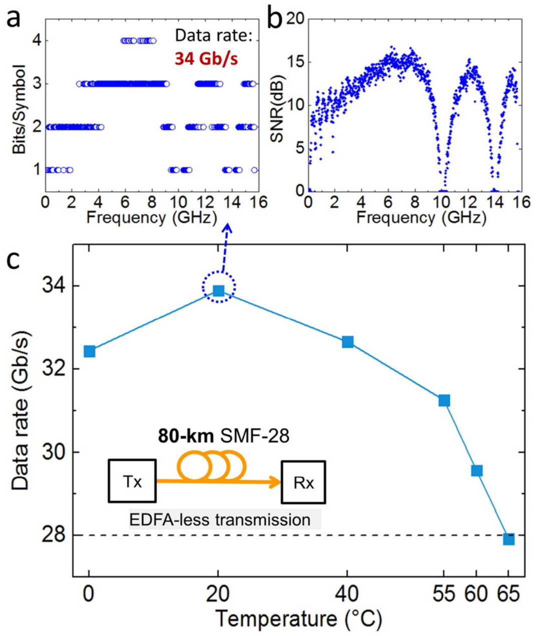

Fig. 2: (a) Bit allocation map and (b) SNR of the demodulated subcarriers after 80-km transmission; (c) Achieved data rate at different temperatures (0-65°C) after 80-km transmission.

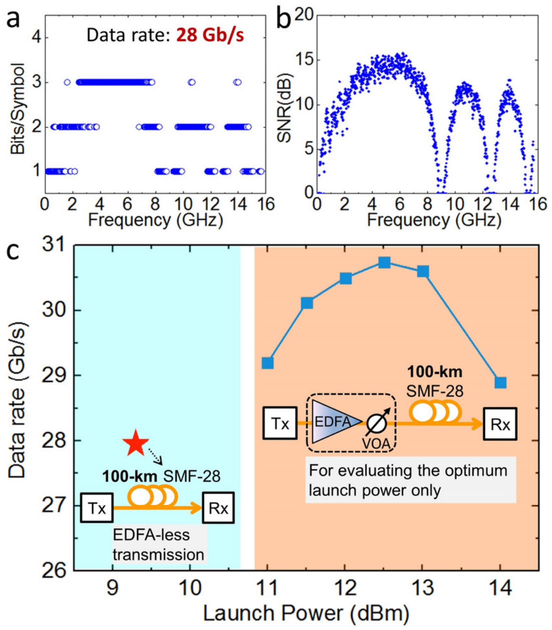

Fig. 3: (a) Bit allocation map and (b) SNR of the demodulated subcarriers after 100-km transmission; (c) Data rate achieved for different launch power. Star marker: without any optical amplification, Square marker: with Tx-side EDFA.

range). The laser was biased at 110 mA for an output power of 9 dBm. An RF signal with a peak-to-peak voltage of 2.3 V w as used to drive the laser.

The DMT waveform samples were generated offline, based on a PRBS of 2^{17}-1 length. The first experiment was carried out using a 32-GS/s digital-to-analogue converter (DAC, Micram VEGA DACII) for waveform generation and a 50-GS/s analogue-to-digital converter (ADC, Tektronix DPO 72004) for digitization at the receiver side. We generated a 15.8-GHz bandwidth DMT signal using an inverse discrete Fourier transform (IDFT) size of 1024, yielding a subcarrier bandwidth of 15.5 MHz. In addition to these experiments, we also show some preliminary results using a state-of-the-art 92-GS/s DAC (Keysight M9505A) for waveform generation, and an 80-GS/s ADC (Agilent DSO-X 96204) for signal digitization. Using this DAC, we generated a 23-GHz bandwidth DMT signal waveform using an IDFT size of 2048, resulting in a subcarrier bandwidth of 11.2 MHz. For both waveforms, a 1.6% cyclic prefix was appended both before and after each DMT symbol. The clipping ratio (the ratio of the clipping level to the root mean square value) of the waveform was 3.2. Digital pre-emphasis was applied to compensate the power frequency roll-off as well as phase distortion.

80 and 100 km lengths of SMF-28 were used to evaluate the transmission performance with received optical powers of -6.6 dBm and -10.3 dBm, respectively. The receiver consisted of a 20-GHz PIN photodiode, followed by 20-GHz-bandwidth RF amplifiers. The electronic signal was digitized and demodulated using offline DSP[4,6]. Bit loading across the DMT carriers was calculated using a QPSK-DMT probe signal with uniform power on all sub-carriers. Our bit-loading algorithm is a modification of Ref. 7 for a maximized total data rate at a fixed BER of 3.8×10^{-3} (the hard decision FEC limit). The data rate in this paper is the pre-FEC data rate that is obtained after removing the overhead for cyclic prefix. Finally, the BER was calculated using error counting of 2^{17}-1 bits.

Experimental Results

A back-to-back data rate of 70 Gbit/s was achieved using the 32-GS/s DAC. After transmission over 80-km SMF-28, the maximum achievable data rate was 34 Gbit/s. Figs. 2a and 2b show the bit allocation map and the corresponding SNRs of the received subcarriers after 80-km transmission, respectively. The achieved data throughput was mainly limited by the thermal noise of the photodiode (received

Tab. 1: Achieved data rate in our simple DM-DD system

Electronics	DAC: 32GS/s ADC: 50GS/s			DAC: 92GS/s ADC: 80GS/s	
DMT signal bandwidth	15.8 GHz			23 GHz	
Transmission distance	Back-to-back	80 km	100 km	Back-to-back	80 km
Achieved data rate (Gbit/s)	**70**	**34**	**28**	**110**	**49**

power of -6.6 dBm) and the dispersion-induced frequency fading around 10 and 14 GHz. The low SNR of the low-frequency subcarriers is due to the laser chirp at low-frequency and the associated dispersion induced fading, as well as the digital pre-emphasis, which trades-off the performance of the low-frequency subcarriers for the benefit of the high-frequency subcarriers[6]. From 0 to 65°C, the achieved data rate after 80 km transmission was above 28 Gbit/s, as shown in Fig. 2c. This shows that the transmitter has the potential to be used in an uncooled package within a 4 × 28 Gbit/s line card, which would offer a compact and low power consumption 100-Gbit/s implementation.

Maintaining the laser at a temperature of 20°C, the fibre length was increased to 100 km with a resultant data throughput of 28 Gbit/s. Thus, the use of a TEC enables an additional 20 km transmission at the 28 Gbit/s data rate (as shown in Table 1). The bit allocation map and corresponding SNRs are shown in Figs. 3a and 3b. Comparing this with the results obtained for 80 km, three dips instead of two are observed due to the additional dispersion. The subcarriers having the highest SNRs achieved only a 3 bits/symbol (8QAM) due to the additional 4-dB loss due to the extra 20 km of fibre.

We also studied the optimum launch power. To reach input powers higher than achievable directly from our transmitter, we used an EDFA and a variable optical attenuator (VOA) at the transmitter output. The optimum launch power for 100-km transmission was found to be 12.5 dBm, which represents a trade-off between the SNR and the fibre nonlinearity. This result indicates that the performance can be improved if the laser can be engineered to have 3 dB higher output power, an entirely feasible proposition.

The achieved data throughput using the 92-Gs/s DAC is shown in Fig. 4. The bit allocation map and SNR values of the subcarrier for back-to-back and 80 km transmission are shown in Fig. 4. A raw data rate of 110 Gbit/s was achieved for back-to-back transmission, decreasing to 49 Gbit/s after 80-km transmission. The rapid performance degradation observed for subcarriers higher than 16 GHz is due to the limited laser modulation bandwidth (3 dB at 16 GHz). In the future, we plan to further engineer the system to achieve >56Gbit/s data rate over 80 km link by using a larger-bandwidth photodiode and a laser with improved output power and modulation bandwidth.

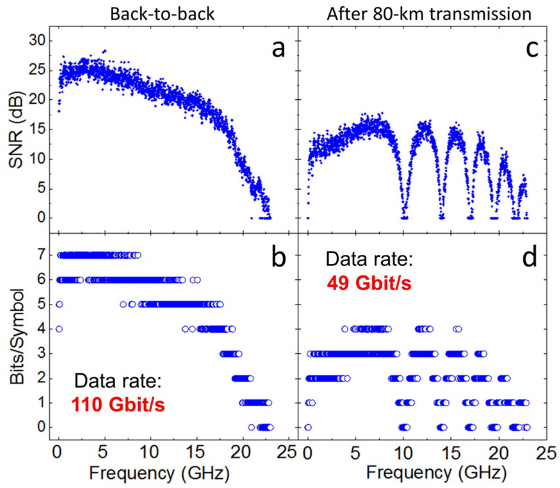

Fig. 4: Data rate achieved using high-speed DAC and ADC. (a) Bit allocation map and (b) SNR of the demodulated subcarriers at back-to-back; (c) Bit allocation map and (d) SNR of the demodulated subcarriers after 80-km transmission.

Conclusions

We achieved an EDFA-less and optical filter-less 28 Gbit/s DM-DD single-channel transmission over 100 km of SMF-28 using an inexpensive discrete mode laser and 16-GHz RF electronics. Large temperature operation range (0-65ºC) was demonstrated for potential uncooled operation. The achieved data rate was increased to 49 Gbit/s when 23-GHz RF electronics was used and laser was stabilized at 20ºC. Based on our analysis such as the optimum launch power characterization in this paper and previously reported DMT results[4], we believe that 56 Gbit/s per wavelength for 80 km transmission can be achieved by further engineering the laser output power and modulation band width. Our system uses the minimum-possible optical hardware, which raises the possibility of a highly practical and low cost solution.

Acknowledgements

This research has received funding from EPSRC Fellowship Grant Agreement No. EP/K003038/1, EPSRC grant EP/I061196X (Photonic Hyperhighway), and UNLOC EP/J017582/1.

References

[1] J.C. Rasmussen, et al., “Digital Signal Processing for Short Reach Optical Links,” Proc. ECOC 2014, Tu.1.3.3., Cannes (2014).

[2] S. Zhou, et al., “Transmission of 2 × 56 Gb/s PAM-4 signal over 100 km SSMF using 18 GHz DMLs,” Opt. Lett., Vol. **41**, no. 8, p. 1805 (2016).

[3] H. Cheng, et al., “10-GHz DML and Adiabatic-Chirp-Involved SSII Cancellation,” Proc. OFC 2016, W1A.6., Anaheim (2016).

[4] T. Tanaka, et al., “Experimental investigation of 100-Gbps Transmission over 80-km Single Mode Fiber using Discrete Multi-tone Modulation,” in Proc. SPIE 8646(86460J-1), (2012).

[5] J. O’Carroll, et al., “Wide temperature range 0 < T < 85 °C narrow linewidth discrete mode laser diodes for coherent communications applications,” Opt. Express, vol. **19**, no. 26, p. B90-B95 (2011).

[6] Z. Liu, et al., “Discrete Multi-tone Format for Repeater-Less Direct-Modulation Direct-Detection over 150 km,” J. Lightw. Technol., DOI: 10.1109/JLT.2016.2555962.

[7] P. Chow, et al., “A Practical Discrete Multitone Transceiver Loading Algorithm for Data Transmission over Spectrally Shaped Channels,” Trans. Commun., vol. **43**, no. 2/3/4, p. 773-775 (1995).