100 Gb/s wavelength division multiplexing four-level pulse amplitude modulated transmission over 160 km using advanced optical fibres

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The authors compare transmission reach of 100 Gb/s four-level pulse amplitude modulated signals over single-span systems constructed with three optical fibre types. They demonstrate reach up to 160 km with fibres having ultra-low attenuation, one with a large effective area.

Introduction: Data centre interconnects (DCIs) is a topic of active research in the optical fibre communication industry. This is largely driven by an increase in content delivery network traffic with average global annual growth reported to be 44% [1], which causes Cloud providers to search for efficient means of connecting data centres. For relatively short-distance (1–3 km) on-campus connectivity between the data centres, large fibre count cable solutions (2000 fibres and above) with cost-effective transceivers rated for 1310 nm are usually preferred. For connecting data centres between two campuses over Metro-like distances, transceivers operating at 1310 nm become inadequate and 1550 nm solutions with wavelength division multiplexing (WDM) must be used. For Metro-DCI applications, the distance between the data centres is determined by availability and cost of real estate, proximity to energy (particularly, renewable) plants, and latency requirements. The ability to increase the distance between those data centres could lead to more cost-effective construction and subsequent operation of a data centre.

Within the 100 Gb/s WDM space, solutions based on coherent detection have for several years been a workhorse in optical fibre communications. These solutions are very effective in situations where fibre is a limited resource, but are also more technologically complex, and therefore may carry a price premium per transponder [2].

An alternative in providing 100 Gb/s connectivity over Metro-like distances is to use four-state pulse amplitude modulation (PAM-4) using two subcarriers, each operating at 28 Gbaud including forward error correction (FEC) overhead. The 100 Gb/s PAM-4 solution approach can also support WDM transmission (up to 40 × 100 Gb/s channels) and is based on direct detection, making it more cost-effective and a smaller-footprint solution compared with coherent counterparts. Previously, 100 Gb/s PAM-4 dual-carrier and 400 Gb/s PAM-4 8-carrier transmission over 80–100 km were shown using regular ITU-T G.652 fibres [3–5]. In this Letter, we perform 100 Gb/s PAM-4 transmission experiments over optical fibres with ultra-low attenuation and also a large effective area in one case, demonstrating reach lengths of up to 160 km. To the best of our knowledge, this is the longest 100 Gb/s dual-carrier PAM-4 transmission distance reported to date.

Experimental set-up: The general experimental set-up for transmission measurements is shown in Fig. 1. A single 100 Gb/s PAM-4 module operating at 1554.95 nm was first coupled together with 38 dummy channels to form the WDM channel plan. The PAM-4 module used in this Letter uses a Silicon Photonics, dual Mach-Zehnder modulator for the transmitter, and dual, high speed Ge PIN photodiodes as part of the polarisation diverse receiver, all integrated onto a single chip. The two wavelengths, constituting the 100 Gb/s signal, are multiplexed and demultiplexed using components integrated on the same chip. The dummy channels were single-wavelength 100 Gb/s channels modulated with 32 Gbaud polarisation multiplexed (PM) QPSK signals by a single I-Q Mach-Zehnder modulator and were spaced 50 GHz between each other. The two closest PM-QPSK channels to the PAM-4 channel were necessarily eliminated in order to avoid interference with the individual PAM-4 wavelengths. The relative channel powers of PAM-4 and PM-QPSK channels were set such that each of the two PAM-4 wavelengths had the same launch power as each 100 Gb/s PM-QPSK channel. After the channels were combined, they were amplified in a two-stage transmitter-side optical amplifier followed by a variable optical attenuator (VOA) to control the launch power in the span of fibre under test. In all tests, a fibre-based dispersion compensation module was used in the mid-stage to pre-compensate the channels. At the receive-side of the single fibre span under test, the channels were amplified again in another two-stage amplifier. An optical tap to monitor optical signal-to-noise ratio (OSNR), a tuneable dispersion compensator, and sometimes another fixed fibre-based compensator depending on span length were located in the mid-stage. After the amplifier, an optical filter with 0.8 nm full width selected the pair of PAM-4 wavelengths for detection in the PAM-4 module.

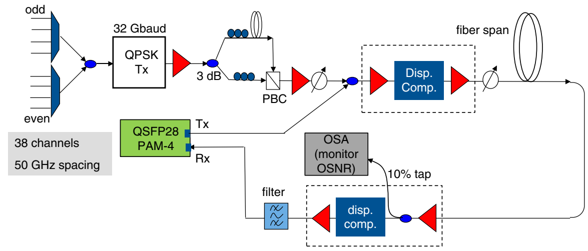

Fig. 1 *Experimental configuration for transmission experiments*

Three optical fibres were tested in the transmission experiments and their characteristics are given in Table 1. In the experiments, we increased the length of the span by splicing on additional fibre lengths until the received signal performance approached a practical Q limit of about 8 dB. Q is calculated from the raw BER as $Q(\text{dB}) = 20\log\left(\sqrt{2}\text{erfc}^{-1}[2 \cdot \text{BER}]\right)$.

Table 1: Optical fibres tested and nominal characteristics

	Corning® SMF-28e+® fibre	Corning SMF-28® ULL fibre	Corning TXF™ fibre
attenuation, dB/km	0.19	0.162	0.168
effective area, μm^2	82	82	125
dispersion at 1550 nm, ps/nm/km	17	17	21

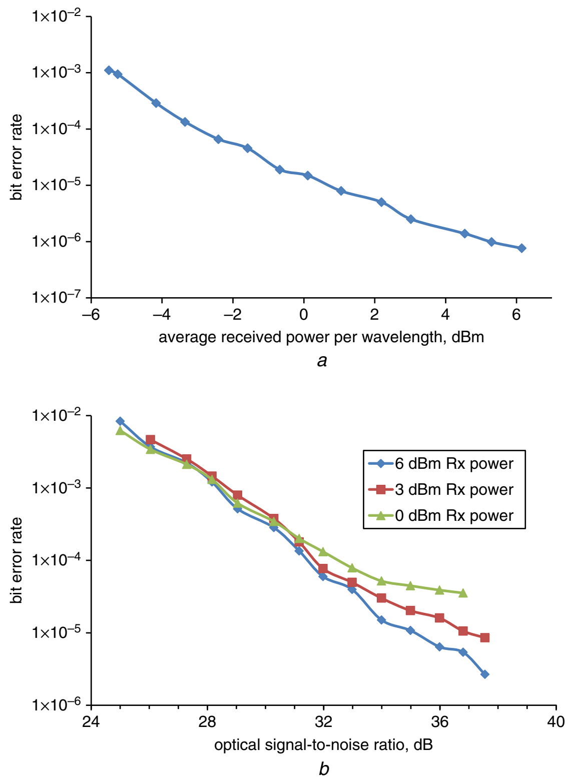

Fig. 2 *Characterisation data of PAM-4 module*

a BER versus received power per wavelength at fixed OSNR
b BER versus OSNR at fixed received power levels

Experimental results: Before beginning the transmission experiments, we first characterised the PAM-4 module. The characterisation measurements involved only the PAM-4 module in simplified set-ups to measure performance as a function of received power and OSNR. The results for BER as a function of received power per wavelength are shown in

Fig. 2*a* and were all obtained with a fixed OSNR value of 39.8 dB. BER values $<1 \times 10^{-6}$ are obtained with received power levels up to about 6 dBm per wavelength. The results for BER as a function of OSNR for several different received power levels are shown in Fig. 2*b*.

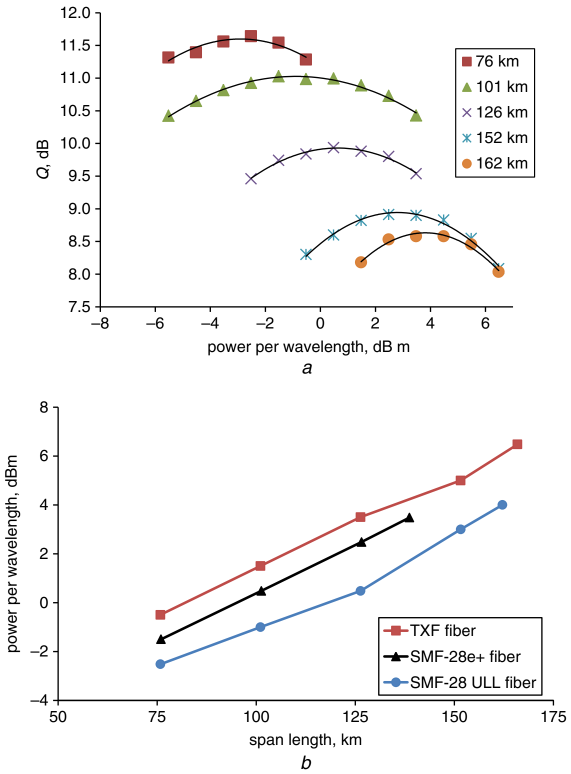

Fig. 3 *PAM-4 transmission data over fibre systems*

a Q versus channel power for SMF-28 ULL fibre spans
b Optimal launch power versus fibre length for each fibre type

For the transmission tests through the different optical fibre spans, and for each different span length, we determined the optimal channel power. This was accomplished by varying the launch power with the VOA at the span input and measuring the raw pre-FEC BER. An example of this data is shown in Fig. 3*a* for the various length systems constructed using SMF-28 ULL fibre. The *y*-axis data in Fig. 3*a* is expressed in terms of *Q*(dB) as derived from the BER data. The data for all the optimal launch powers determined are given in Fig. 3*b* over the range of span lengths tested for each fibre type.

A summary of the transmission performance measurements is shown in Fig. 4 with *Q*(dB) measured from pre-FEC BER values (all transmission was error-free, post FEC) at the optimal launch power given as a function of span length for each fibre type. The results show that all fibres have similar performance up to about 100 km, with a small advantage measured for SMF-28 ULL fibre. Beyond 100 km, there is a separation in the performance and reach obtained between the standard single-mode fibre and the two ultra-low loss fibres. The SMF-28 ULL and TXF fibres perform very similarly to each other and allow maximum reach lengths up to at least 160 km with at least 8.5 dBQ, ~17% further than SMF-28e+. Span lengths of 125 km are possible with *Q* values of 10 dB for both fibres. Longer reach lengths can potentially be applied to allow larger distances between data centres, possibly resulting in lower land acquisition costs. The measured OSNR values for each fibre are also shown in Fig. 4 and illustrate comparable performance with OSNR values ≥30 dB out to at least 150 km for the two advanced fibre systems. Finally, to approximate fully-loaded systems with 40 PAM-4 channels (80 wavelengths), we measured the BER of each signal with 3 dB lower received power. We found only about 0.5 dBQ penalty at each distance relative to the data in Fig. 4 for each fibre type.

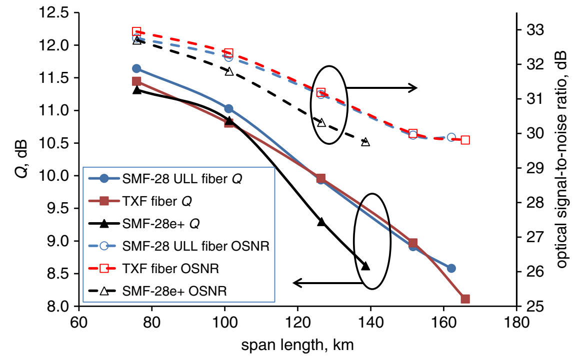

Fig. 4 *Q and OSNR versus span lengths for each fibre*

Conclusion: We have investigated the maximum reach of a 100 Gb/s PAM-4 module for three different fibre types. The PAM-4 wavelengths were transmitted in the system along with 38 other 100 Gb/s PM-QPSK channels. We found a maximum reach of ~160 km for both SMF-28 ULL and TXF fibres at 8.5 dBQ, which we believe is the longest reported reach for this type of transceiver. At 10 dBQ, both fibres provided reach lengths of about 125 km. The long span lengths afforded by these fibres may allow greater distances between data centres.

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One or more of the Figures in this Letter are available in colour online.

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