

# Crosstalk Analysis of 32-Core Dense Space Division Multiplexed System for Higher Order Modulation Formats Using an Integrated Cladding-Pumped Amplifier

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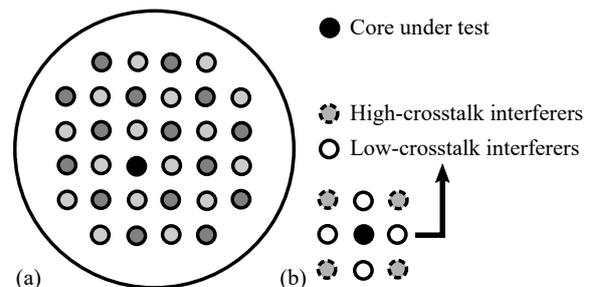
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**Abstract** We analyse the crosstalk performance of a fully integrated inline amplified 32-core link for 100G QPSK, 150G 8QAM, 200G 16-QAM, and 250G 32QAM in a recirculating loop. Transmission distances over 1000 km are confirmed for 8-QAM and QPSK channels.

## Introduction

In the recent years, multicore fibre (MCF)-based transmission systems have drawn significant research interest to offset the capacity crunch of single-mode fibre. High-core-count integrated multicore amplifiers are essential to construct compact and energy-efficient long-haul space-division multiplexed (SDM) transmission systems. Previously, it has been reported that transmission distances over 1000 km were achieved using a shared core-pumping 19-core erbium-doped fibre amplifier (EDFA)<sup>1</sup>. Compared to core-pumping amplification schemes, cladding-pumped amplifiers are very attractive due to their compactness and superior power-efficiency. Several long-haul transmission experiments using a 7-core cladding-pumped EDFA<sup>2</sup> in the L-band, and a 7-core side-coupled cladding pumped erbium-ytterbium-doped fibre amplifier in the C-band<sup>3</sup> have been demonstrated. For the realization of dense multicore transport systems, the low-crosstalk performance of a heterogeneous 32-core MCF<sup>4</sup> has been analysed and a reach of more than 1000 km for a transmission experiment has been reported<sup>5</sup>. Recently, the feasibility of a compact side-coupling cladding-pumped 32-core amplifiers with multicore isolators has been shown for an inline repeated transmission<sup>6</sup>. In this paper, we demonstrate for the first time a dense SDM transmission performance over 1000 km using both the fully integrated 32-core inline amplifier

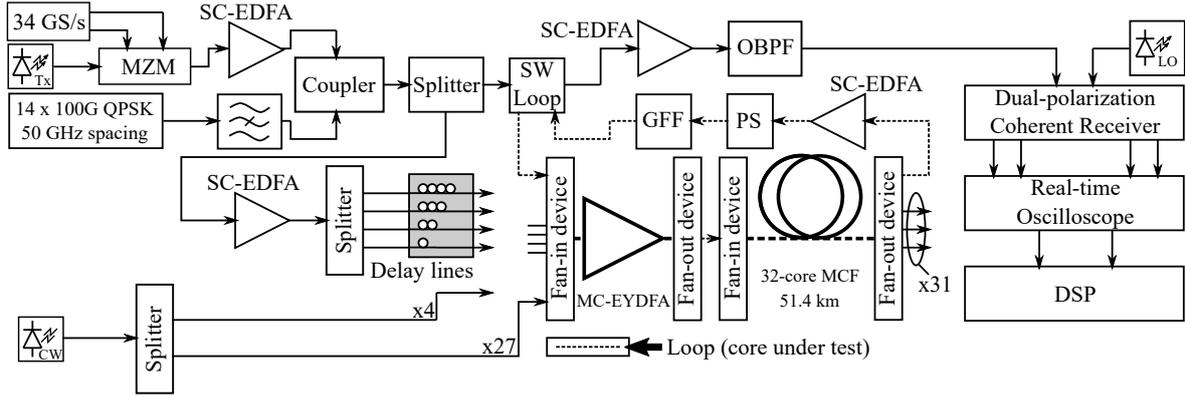


**Fig. 1:** (a) Cross-sectional view of the heterogeneous 32-core MCF (different colours represent different refractive indices). (b) Small sample of cores illustrating the crosstalk contributions from cores around the core under test, expected to exhibit a worst-case performance.

and a 51.4 km 32-core MCF. We evaluate the crosstalk performance of an m-QAM channel in detail to verify the achievable reach and spectral efficiency of the 32-core inline amplified link.

## 32-core transmission link

To analyse a dense multicore transmission, we use an improved version of the first integrated 32-core cladding-pumped erbium-ytterbium-doped fibre amplifier (MC-EYDFA)<sup>6</sup> and a heterogeneous trench-assisted 32-core fibre with a length of 51.4 km<sup>5</sup>. The current version of the MC-EYDFA improves the overall performance by means of a 965 nm pump wavelength, which is away from the Yb-ions absorption peak of 975 nm and, therefore, reduces the core-to-core absorption variation significantly. This, in turn, results in a uniform core-to-core gain and a better noise figure performance. The second-generation



**Fig. 2:** Experimental setup using an integrated 32-core link in a recirculating loop.

32-core MC-EYDFA has a maximum variation in gain and noise figure of 2 dB, in contrast to the previously reported amplifier, for which the variation was around 5 dB. The MCF, whose core layout is shown in Fig. 1, displays two different refractive indices for alternating cores in order to reduce crosstalk. As shown in the figure, the directly adjacent cores have a different refractive index which reduces their crosstalk contribution to  $< -45$  dB, making them low-crosstalk interferers. The highest crosstalk contribution ( $-36$  dB cumulative) comes from the 4 diagonal neighbouring cores. In the following, the cores that exhibit a higher crosstalk inference will be denoted as neighbouring cores. Furthermore, the transmission line contains two sets of FI/FO couplers, whose crosstalk contribution from the neighbouring cores is  $< -55$  dB per set, to let the signals in and out of the integrated multicore components.

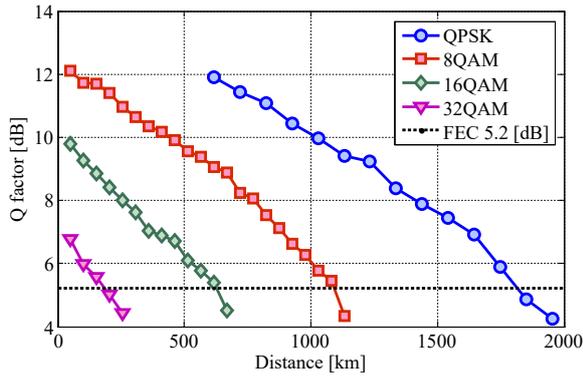
### Experimental setup

Figure 2 shows the experimental setup used to evaluate crosstalk penalties in a dense SDM system. At the transmitter, 15 WDM channels are generated in a 50 GHz grid ranging from 1555 nm to 1561 nm. The test channel, located at 1558.17 nm, is modulated using a variety of m-QAM modulation formats, whereas the neighbouring channels carry 100 Gbit/s QPSK data. Before the neighbouring channels are coupled with the test channel, a notch filter is used to remove noise at the test channel's position in the spectrum. The signal is then split into two copies: one for the core under test and one for the neighbouring cores. The latter is further split and delayed to produce de-correlated copies of the original WDM signal. In order to prevent spurious lasing from the flat end of the fibre in fan-in/fan-out couplers, we provide an unmodulated out-of-band

continuous-wave light source (CW) at 1550 nm. This signal is split and fed to the remaining MCF cores with a power of  $\sim -3$  dBm per core. For the reference crosstalk-free experiments, the CW signal is used as input to the neighbouring cores as well. The multicore link consists of an integrated MC-EYDFA that compensates the loss of the fibre, a 51.4 km 32-core heterogeneous MCF, and two sets of fan-in/fan-out couplers to simplify access to the devices for testing. The main advantage of this setup is the possibility of a more complete analysis of the MCF system at the cost of introducing additional crosstalk. Only the signal in the core under test goes into the recirculating loop; the signals from the rest of the cores just go through a straight-line multicore link. In the loop structure, the average fibre input power of  $-3$  dBm/ch was set to evaluate the crosstalk without nonlinear penalty for all modulation formats. After the multicore elements, a single-core erbium-doped amplifier (SC-EDFA) is inserted to compensate for the losses produced by the rest of the elements in the loop: a low-speed polarization scrambler (PS), a gain-flattening filter (GFF), and the loop switches (SW Loop). After the loop, a SC-EDFA boosts the signal before an optical bandpass filter (OBPF) extracts the test channel. The channel at 1558.17 nm is fed to a coherent receiver and the electrical signal detected by a real-time sampling oscilloscope. Digital signal processing (DSP) is performed in the following order: resampling to 2 samples/symbol, frequency-domain chromatic dispersion compensation, carrier frequency estimation, 2-by-2 multiple-input multiple-output equalization, clock and phase recovery.

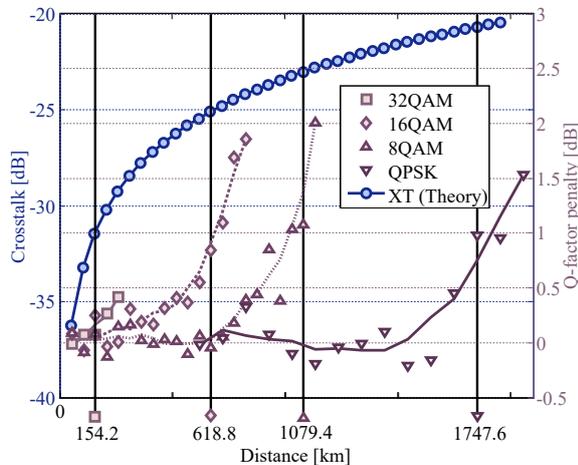
### Results

To analyse and characterize the effect of crosstalk on the data transmission over the multicore link, we observe the core under test



**Fig. 3:** Measured Q-factor at various distances for different modulation formats.

highlighted in Fig. 1. The Q-factor values corresponding to various transmission distances for a test channel carrying 100 Gbit/s QPSK, 150 Gbit/s 8QAM, 200 Gbit/s 16QAM, and 250 Gbit/s 32QAM can be seen in Fig. 3. In this experiment, we have lit up the neighbouring cores with the de-correlated copies to observe the achievable reach for a scenario with crosstalk. Assuming a soft decision forward error correction (FEC) threshold of  $Q = 5.2$  dB, we report reaching distances of 154.2 km (32QAM), 616.8 km (16QAM), 1079.4 km (8QAM), and 1747.6 km (QPSK).



**Fig. 4:** Q-factor penalties compared to crosstalk-free transmission for the different m-QAM modulation formats (right axis) and theoretical crosstalk -XT (Theory)- for corresponding transmission distances based on crosstalk measurements of the components (left axis).

Repeating the previous experiment by propagating the CW signals also in the neighbouring cores instead of the de-correlated copies, we are able to define a benchmark for a crosstalk-free transmission. We define the crosstalk penalty as the difference in Q-factor for a transmission experiment with and without crosstalk. This is observed in Fig. 4, where we show the Q-factor penalty and the expected crosstalk level caused by the MCF and the two sets of fan-in/fan-out

couplers as a function of the transmitted distance (left). The solid vertical lines mark the corresponding achieved transmission distances using a given m-QAM modulation format. We can observe that QPSK, 8QAM, and 16QAM exhibit a Q-factor penalty of  $\sim 1$  dB at the maximum transmitted distance, which shows that the accumulated crosstalk is large enough to visibly degrade the signal quality. On the other hand, crosstalk affecting 32QAM produces a Q-factor penalty of  $< 0.25$  dB after 154 km.

## Conclusions

We have transmitted, respectively, one 100 Gbit/s QPSK, 150 Gbit/s 8QAM, 200 Gbit/s 16QAM, and 250 Gbit/s 32QAM channel at 1558.17 nm, as the centre wavelength in a WDM signal consisting of 15 channels in a 50 GHz grid. Using an integrated 32-core inline repeated link in a recirculating loop, we achieved transmission distances of 1747 km, 1079 km, 616 km, and 154 km, respectively. Experimental results show that QPSK, 8QAM, and 16QAM exhibit similar Q-factor penalties (1 dB) around those distances, whereas 32QAM is affected by a crosstalk-induced Q-factor penalty of  $< 0.25$  dB due to its short reach.

## Acknowledgements

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