

108 Tb/s Transmission over 120 km of 7-Core Multicore Fiber Link with Integrated Cladding Pumped Multicore Amplifiers

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Abstract By employing time-domain hybrid modulations we maximize the throughput over a multicore fiber link. Modulation scheme ratio is adjusted according to the available OSNR at each spatial and wavelength channel achieving a net spectral efficiency of 39.27bit/s/Hz after 2x60km transmission.

Introduction

Multicore fiber transmission systems are very attractive for throughput-hungry applications like inter- and intra- data center connections. In these systems cost and power savings can be realized by using integrated multicore cladding pumped amplifiers¹. Cladding pumped multicore amplifiers require only one multimode laser-diode for amplification of all cores, making them relatively smaller in size and attractive for commercial applications².

In order to minimize cost per transmitted bit, data-rate over a given link should be maximized. Employing coherent optical transmission technology, line rates in excess of 200 Gb/s per wavelength can be achieved by classical modulation formats such as e.g. 16QAM, 32QAM, 64QAM, etc.². To maximize the throughput over a given multicore transmission system, the order of the QAM formats can be adapted for each wavelength channel as well as for each core according to the available SNR at the receiver. However, classical modulation formats exhibit large differences in required signal-to-noise ratio (SNR) among each other. Hence, by using classical modulation formats,

only a coarse optimization of the throughput over multicore transmission systems can be achieved. Advanced modulation techniques as e.g. time-domain hybrid QAM (TDHQ)³⁻⁵, frequency-domain hybrid modulation⁶, constellation shaping and multi-dimensional modulation formats provide much finer granularity in required SNR and achievable data-rates, keeping symbol rate and code rate fixed. By employing advanced modulation formats, throughput can be precisely maximized and cost per bit can be further reduced.

This paper demonstrates the use of TDHQ to maximize throughput over a 120 km long multicore transmission link with cladding pumped multicore fiber amplifiers.

Experimental Setup

Fig. 1 shows the experimental multi-core transmission setup. The multi-core link, embedded in a recirculating loop, consists of one 60-km span of 7-core fiber and two cladding-pumped erbium-ytterbium-doped 7-core fiber amplifiers (MC-EYDFA). Fiber fan-in/fan-out couplers based on free-space optics are used to integrate the multi-core link in the

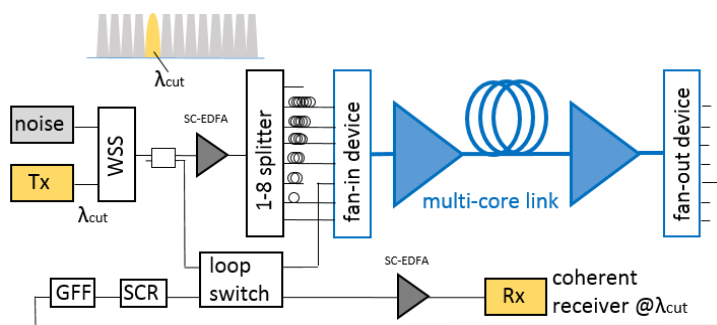


Fig. 1: Experimental setup. WSS: wavelength selective switch, GFF: gain flattening filter, SCR: pol. scrambler

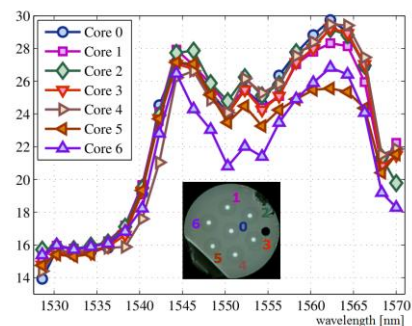


Fig. 2: Overall gain profile of the cascaded multi-core EYDFAs and multi-core fiber. Inset: A microscopic image of 7-core fiber.

recirculating loop. The pump currents for both amplifiers are optimized by considering best performance for middle core as well as for two outer cores and taking the average value³.

The amplification band of the MCF amplifier covers the wavelengths 1566.723 nm to 1544.924 nm (or 191.35 THz to 194.05 THz) making a 2.75 THz frequency band available for transmission, corresponding to 55 channels at 50 GHz channel spacing. The gain profile for these channels through the different cores over the complete link is shown in Fig. 2. Due to large difference in gain over wavelength and cores, the OSNR after transmission is also different for each wavelength and spatial channel. In such a case, using a single modulation format with fixed symbol-rate and code rate can only provide suboptimal throughput.

The input optical signal in each core consists of a channel under test (CUT) multiplexed with ASE noise to emulate wavelength division multiplexed (WDM) transmission⁷. CUT and ASE are multiplexed employing a wavelength selective switch (WSS) with 50GHz per channel bandwidth. Prior to input, WDM optical signal of each core is properly de-correlated by applying different delays in their optical path. In order to evaluate performance over different wavelength channels, Tx/Rx lasers as well as WSS are tuned at the desired wavelength.

The loop setup is so configured that the optical signal circulates twice through the core under test emulating 120 km transmission link. The optical loop consists of a gain flattening filter as well as a polarization scrambler to balance the optical spectrum and evenly distribute polarization dependent effects, respectively. Apart from core under test, the optical signals from all the neighboring cores are passively terminated after fan-out. After transmission over 120 km (two loops) of 7-core fiber, the BER was evaluated for all cores and wavelengths. After demodulation using an integrated coherent receiver, the signal was sampled with a 23-GHz bandwidth real-time oscilloscope. The sampled signal was evaluated by offline DSP processing, which consists of CD equalization, carrier frequency and phase recovery, polarization demultiplexing, channel equalization, clock recovery and BER evaluation.

Measurements, Results and Discussion

The signal samples of the CUT were generated offline. The generated symbol stream was up-sampled to 2 samples per symbol and spectrally shaped using a root-raised cosine filter with roll-

off 0.2. On top of the payload data, the CUT includes 4% OTN overhead, 3% overhead for training and pilot symbols, and 25% FEC overhead. The gross symbol rate was kept constant at 35 Gbd in order to exploit the full analog bandwidth of the components.

The received OSNR after 120 km transmission was in range of 21 dB to 26 dB. Based on the available OSNR for each spatial and wavelength channel, TDHQ format was selected from a defined set. In this analysis we used 64QAM and 16QAM modulations in time domain hybrid frame. By controlling the ratio of 64QAM symbols to 16QAM symbols in time domain hybrid frame, the net data-rate for each channel could be configured quasi continuously between the two extremes 209 Gb/s (16 QAM only) and 314 Gb/s (64 QAM only). While in principle many more formats could be supported, in the experiment we used only the ratios of (64QAM, 16QAM) = {(90%, 10%) (80%, 20%) (67%, 33%) (50%, 50%) (33%, 67%) (25%, 75%)}. The back to back performance curves for the underlined cases are shown in Fig. 3. BER performance

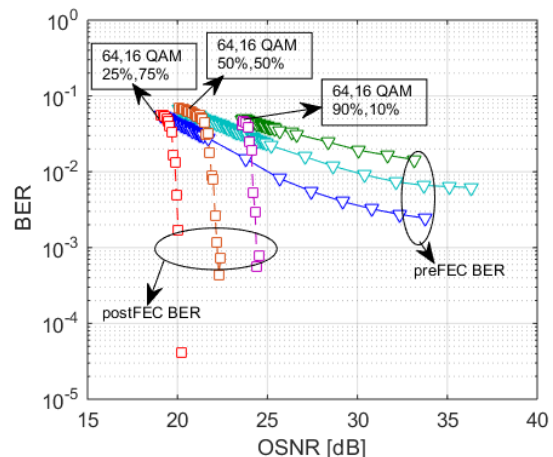


Fig. 3: Back-to-back performance

before FEC as well as after 20 FEC iterations are shown. It can be observed that required OSNR for error free performance of considered formats lies in range of >20.5 dB to >25.2 dB which coincides well with the available OSNR after 120 km transmission.

In order to select an appropriate scheme to be used at a given core and wavelength, first a monitoring signal is sent at the CUT wavelength to determine the received SNR. The modulation scheme ratio was then adjusted such that pre-FEC BER was expected slightly below the FEC threshold. Following this procedure for all wavelengths and cores, always maximum data-rate for each channel was transmitted. Consequently, data throughput over the whole link was optimally maximized.

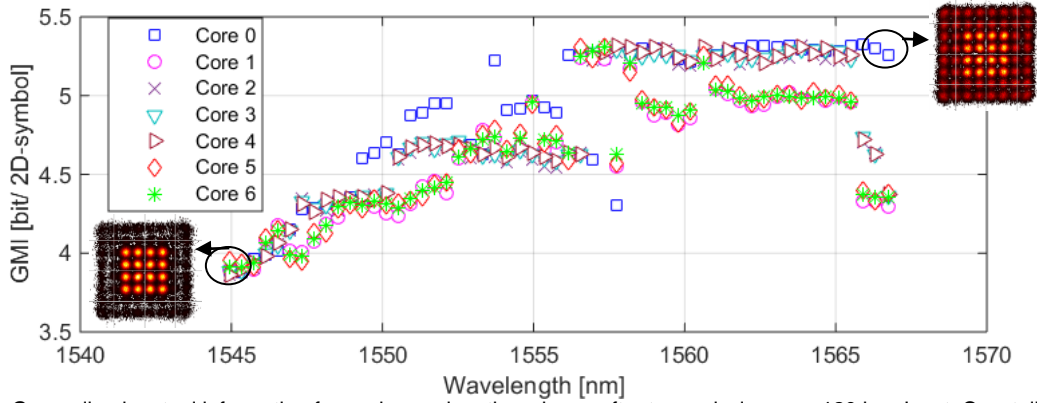


Fig. 4: Generalized mutual information for each wavelength and core after transmission over 120 km. Inset: Constellation diagrams for 64QAM/16QAM = (90%, 10%) and (25%, 75%) cases.

After transmission through the link, all the wavelength and spatial channels were detected error-free employing 20 FEC iterations. The pre FEC BER for different channels lie in range of 3.1×10^{-2} to 4.5×10^{-2} . The generalized mutual information (GMI)⁸ for all the transmitted channels is evaluated after 120 km MCF transmission and the corresponding results are shown in Fig. 4. It can be observed that larger throughput for all cores was achieved at longer wavelengths. Furthermore, cumulatively, the central core (core 0) could carry larger throughput than the rest because of larger gain for this core from the amplifiers. The net throughput for each core after 120 km transmission is summarized in table 1.

Tab. 1: Net data throughput for each core after 120 km MCF transmission.

Core	Net data throughput [Tb/s]
0	15.76
1	15.13
2	15.48
3	15.48
4	15.48
5	15.13
6	15.13
Total	107.59

Conclusions

We optimized data throughput over a multicore fiber link with integrated cladding pumped amplifiers employing suitable time domain hybrid modulation schemes after sensing received SNR for each channel. Consequently, a net data throughput of 107.59 Tb/s was transmitted over a 2x60 km link. In each core, 55 WDM channels with 50 GHz spacing were

transmitted which translates to a net spectral efficiency of 39.27 bit/s/Hz.

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