160 Gb/s OTDM Networking using Deployed Fiber

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***Abstract*— We report a 160 Gb/s OTDM network comprising switching and demultiplexing through field deployed fiber. The 160 Gb/s signal was obtained by time-interleaving 16 channels of a 10 Gb/s signal. The add-drop node was realized by using a gain-transparent operation of a semiconductor optical amplifier (SOA). A subharmonic clock recovery with a pre-scaled electro-optical phase locked loop employing an electroabsorption modulator was applied. An OTDM receiver employed a four-wave mixing principle in an SOA. The impact of fiber chromatic and polarization mode dispersion is discussed. Switching and demultiplexing performance are shown for a fiber link of 275 and 550 km, respectively. Excellent operation of clock recovery, drop-through-add function, and transmission was achieved.**

***Index Terms*— Time division multiplexing, demultiplexing, optical switches, ultrafast optics, semiconductor optical amplifiers, electroabsorption**

I. Introduction

Future optical data transmission will change from todays point to point connections towards transparent meshed optical networks. At the same time the increasing bandwidth demand will require much higher transfer capacities per fiber than current ones. It is still an open issue whether the increase of capacity will be accomplished by a higher number of wavelengths per fiber or by higher bitrates per wavelength or - most probably - a combination of both. 160 Gb/s optical time domain multiplexing (OTDM) is a promising candidate for cost effective optical networks. For data rates of 80, 160 Gb/s or more per wavelength OTDM has to be applied since electronic processing is not possible yet for such high data rates. However, the flexibility of transparent optical networks which will be implemented for the wavelength multiplexing technology (WDM) within the next years should be conserved when introducing OTDM in addition to the WDM technology [1]. This implies the need of additional optical elements in the network: time domain add-drop multiplexers (TD-ADMs). In an OTDM add-drop node a low-bitrate single data channel has to be separated (drop function) from an incoming high-bitrate data stream. Simultaneously, the remaining data channels have to be left undisturbed (through function) and the time slots of the dropped channels have to be depleted sufficiently. In these time slots new channels can be added (add function). The use of TD-ADMs or even time domain optical cross connects, in meshed OTDM networks implies the need of additional elements in the network nodes to compensate for differential time shifts between different paths through the network [2, 3]. As these timing elements are not necessary in todays WDM networks they add another layer to the architecture of ADM network nodes. In addition, to be able to merge two OTDM paths with randomly occupied channels permutation of the channels will be necessary in order to prevent collisions.

Techniques enabling 160 Gb/s transmission and demultiplexing are described in [4] and a field transmission experiment in [5]. Recently, back-to-back (B2B) TD-ADM experiments have been reported for 16×10 Gb/s [6] and 4×40 Gb/s [7]. A first TD-ADM network experiment with clock recovery (CR) and transmission over 300 km spooled fiber is reported in [8]. A summary of the first fully working TD-ADM field experiment over 275 km deployed fiber has been given in [9].

In this paper we report in detail about 160 Gb/s field experiments carried out on deployed fiber in BT's network in the United Kingdom. First we describe the fundamental components used throughout the experiments and give details about the compensation techniques applied. Then we show the results of 160 Gb/s OTDM networking experiments over 275 km of G.652 standard single-mode fiber (SSMF) consisting of three nodes (transmitter, TD-ADM, and receiver) and transmission experiments over up to 550 km SSMF. Finally, we present concepts and possible architectures of TD-ADM nodes necessary to implement a fully flexible meshed OTDM network.

II. Enabling Technologies

A. Transmitter

A 160 Gb/s data stream was generated by interleaving copies of a 10 Gb/s return-to-zero (RZ) signal (duty cycle 2%), which was generated in an erbium-glass oscillator pulse generating laser (ERGO-PGL) with a pulse width of 2 ps (full-width at half maximum FWHM sech^2), a wavelength of 1551.7 nm and a repetition rate of 9.95328 GHz. The signal was modulated with a 2^7-1 pseudo random bit sequence (PRBS) in an external Mach-Zehnder-modulator (MZM). Interleaving was achieved with four polarization maintaining fiber (PMF) based delay and add stages. To get a realistic data stream at 160 Gb/s the delay was adjusted such that a 2^7-1 PRBS at 10 Gb/s at the input results in a 2^7-1 PRBS at 160 Gb/s at the output. The multiplexer stage is PRBS-maintaining only for 2^7-1 pattern length. Due to the long fibers in the transmitter and no thermal stabilization, this

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subsystem was a main source of instability for the measurement. The add channel was generated with a fiber ring laser (9.95328 GHz 2.2 ps FWHM sech^2) modulated with a 2^7-1 PRBS in an external MZM. Wavelength, amplitude, phase, and polarization of the added channel were adjusted to meet the transmitted signal in the through port. The combination of the data streams was realized by a passive coupler.

B. Receiver

Four-wave mixing (FWM) in an SOA was used as demultiplexer [10]. A second erbium glass solid state laser (control-laser) which generated pulses of 2 ps FWHM sech^2 at a wavelength of 1543 nm was synchronized via CR to the 16$^{\text{th}}$ subharmonic of the 160 Gb/s data signal. The pulses of the control laser were superposed with the data signal. The pulse power in both signals have been set to be equal, resulting in a 9 dB difference in average power level. The relative phase of the two signals could be adapted with a free space delay line. The wavelength configuration relative to the gain maximum of the SOA has been optimized as described in [11]. The FWM product was filtered with a narrow band filter and given onto a standard amplified 10 Gb/s receiver. Bit error rate (BER) curves were measured by attenuating the input signal into the 10 Gb/s receiver. Eye pattern diagrams were recorded with an optical sampling oscilloscope (OSO).

C. Clock Recovery

Figure 1 presents schematically the pre-scaled CR used built entirely from standard commercial components. This scheme

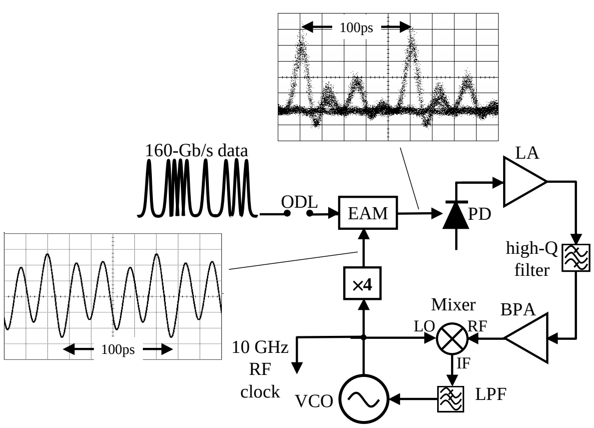

Fig. 1. A schematic of subharmonic clock recovery utilizing a single unidirectional EAM in an electro-optical PLL.

is a simplified form of the scheme presented in [12]. An input 160 Gb/s OTDM signal enters an electro-optical phase-locked loop (PLL) oscillator through an optical delay line (ODL) and a 40 GHz electroabsorption modulator (EAM). The EAM output is detected by a photodetector (PD), amplified by a limiting amplifier (LA), and bandpass filtered by a combination of a high-Q filter ($Q\sim$1000) and a bandpass amplifier (BPA). A radio frequency (RF) mixer combines the filtered data signal with a locally generated 10 GHz clock of a voltage-controlled oscillator (VCO) for phase detection. The resulting phase error is processed in an active lowpass filter (LPF), and is subsequently used to drive the VCO. The gating signal is derived from the VCO output, which is then quadrupled ($\times 4$) to 40 GHz. The quadrupler consists of two doublers in cascade, each sandwiched by high-gain amplifiers. For normal operation ($\sim$5$-$8 dBm input power), the amplifiers produce sufficient power to saturate the doublers, resulting in a 40 GHz sine signal with a constant amplitude. However, if the input power is below threshold ($<$3 dBm), the power to the first doubler is too low to switch on the amplifier, which in turn provides too little power for the second doubler. As a consequence the fundamental input bleeds through, causing the output being an oscillating signal at 40 GHz with strong amplitude components at a 100 ps interval (see the $\times 4$ output in Fig. 1). This low-input power effect is further exploited by the nonlinear characteristics of the EAM. A 160 to 40 Gb/s demultiplexed signal by the EAM, which has a strong 10 Gb/s component is also depicted in Fig. 1. We measured the carrier-to-noise ratio at 10 kHz offset 92 dBc/Hz. Integrating the single sideband phase noise over an interval 10 kHz to 10 MHz results in a root mean square (rms) time jitter of around 205 fs confirmed by a digital communication analyzer with precision time base. Important characteristics of this CR concept are shown in Fig. 2. For EAM input powers between -4 and

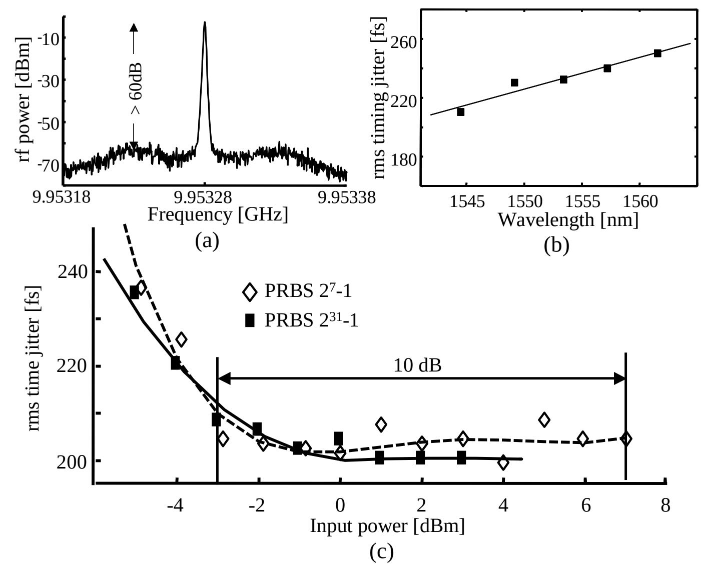

Fig. 2. Measured characteristics of the recovered clock signal: (a) electrical spectrum, and rms time jitter versus (b) wavelengths, and (c) input powers for two types of PRBS.

+6 dBm, i.e 10 dB input dynamic range, the rms time jitters were 200 to 210 fs, which correspond to the VCO jitter performance. We measured time jitters of less than 250 fs over the wavelength range 1544$-$1562 nm, also for a PRBS length of $2^{31}-1$, proving the CR scheme to be nearly pattern insensitive. It should be noted that with this long pattern length the PRBS character of the data signal was not preserved. The design was also verified to be polarization independent. The CR holding range examined by adjusting the base rate once locking was a few MHz, which we believe is limited by the bandwidth of the operational amplifiers in the LPF. This CR setup is attached to the TD-ADM and the receiver.

D. Add-Drop Multiplexer

An SOA based gain transparent ultrafast nonlinear interferometer (GT-UNI) was used as TD-ADM. A schematic of the GT-UNI switch is presented in Fig. 3. This interferometric

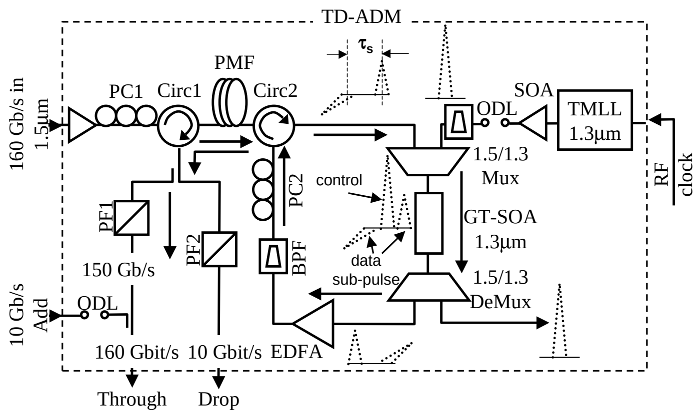

Fig. 3. A schematic of the time-domain add-drop multiplexer based on gain transparent operation of an SOA in an ultrafast nonlinear interferometer.

switch is a modified version of the one presented in [13]. In the GT-UNI switch each pulse of the 160 Gb/s data stream was split in time τ_s into two orthogonally polarized pulses by a high birefringent fiber, such as a PMF [8, 9, 14]. In our experiments, $\tau_s = 4$ ps. These sub-pulses are inserted into a 1.3 μm gain transparent SOA. To realize a drop function, in between these two sub-pulses a 1.3 μm 3 ps (FWHM sech^2) control pulse is inserted. In the GT-SOA the control pulse causes a nonlinear phase shift only to the trailing sub-pulse. The phase of the leading sub-pulse remains unchanged. The

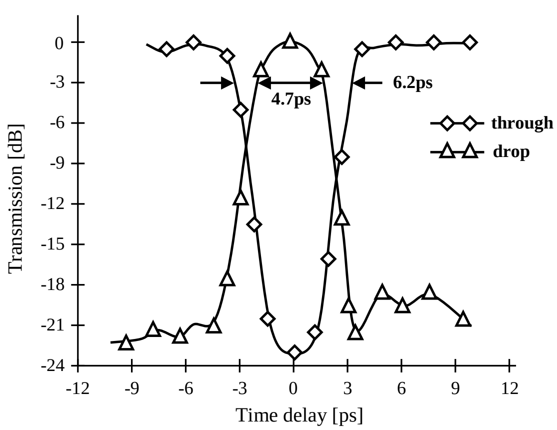

Fig. 4. Switching window for drop and through function of the GT-UNI switch.

polarization adjusted sub-pulses were re-sent into the same PMF to revert the time splitting, forming a single pulse. The polarization state of this pulse is determined by the phase difference of two sub-pulses. Since an orthogonal polarization rotation is practically difficult to obtain [8], the drop and through function are optimized separately by splitting the output in two branches and by using polarization filters (PFs). The PF is formed by a combination of a polarization controller (PC) and a polarization beam splitter (PBS). All PCs are manually controlled. After one 10 Gb/s channel is dropped, a new 10 Gb/s channel can be added to the 15×10 Gb/s remaining channels. The switching window of the TD-ADM, as shown in Fig. 4, was 4.7 ps for the drop and 6.2 ps for the through function.

E. Compensation Techniques

1) Chromatic Dispersion Effect: As is known, the chromatic dispersion effect increases with the signal bit rate [15]. We carried out transmission modeling to investigate the dispersion tolerance at 160 Gb/s, systems with different number of spans and span launch power were considered. Figure 5 shows the simulated eye penalty for different amount of residual dispersion. At lower signal powers, the self-phase

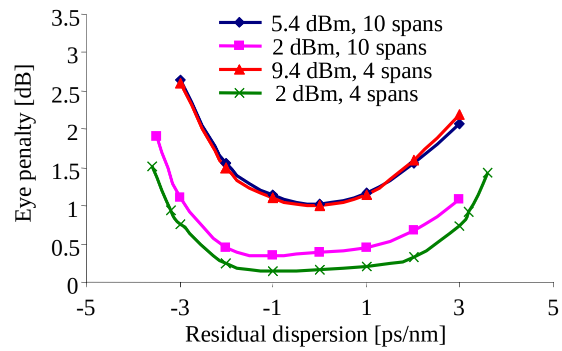

Fig. 5. Simulation results on impact of the residual dispersion on 160 Gb/s signal for different launch powers and span counts. The penalty for 0 ps/nm residual dispersion results from the fiber nonlinear effects.

modulation (SPM) effect is low, as a result residual dispersion within a window of approximately ± 3 ps/nm only causes small additional penalty. At higher span launch powers, the dispersion tolerance is slightly less due to the more significant SPM effect. Therefore, the residual dispersion needs to be kept within ± 3 ps/nm in order to minimize the dispersion penalty. For high powers and high span numbers even an enhanced adjustment of residual dispersion is necessary.

2) Dispersion Slope Effect and Fiber Imperfections: A 160 Gb/s signal has a broad spectrum with a signal bandwidth of about 3 nm using the RZ format. Due to the dispersion slope, the dispersion values are slightly different across wavelengths within the 160 Gb/s signal bandwidth. This accumulates along the transmission. Figure 6 shows the modeling results on the impact of the imperfect dispersion slope compensation, where the chromatic dispersion is fully compensated and the dispersion slope value of the dispersion compensation modules (DCM) in each span is adjusted to achieve different levels of in-line dispersion slope compensation. First, if the non dispersion slope compensating DCM is used, only one transmission span is possible limited by the dispersion slope effect. As the dispersion slope compensation deviates from 100% compensation, the number of spans achievable for a 1 dB eye penalty reduces due to the additional penalty caused by the incomplete compensation of dispersion slope. To obtain a reasonable number of spans the mismatch

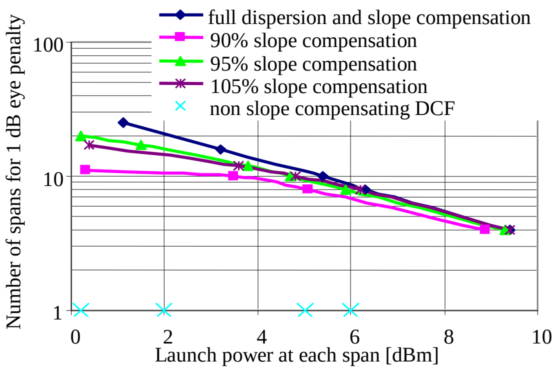

Fig. 6. Simulation results on impact of the imperfect in-line dispersion slope compensation, dispersion is 100% compensated.

needs to be kept within 5%. Figure 7 shows the simulated tolerance of the 160 Gb/s to the residual dispersion slope at the end of the transmission. We considered a 5 span system

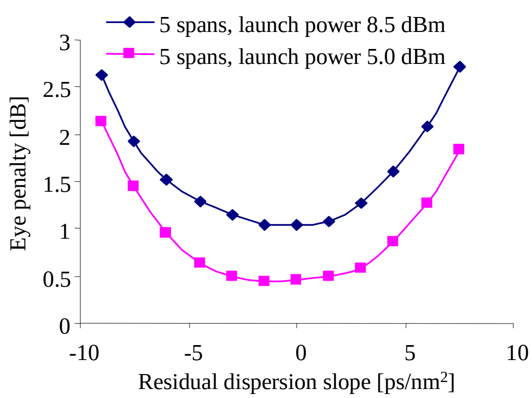

Fig. 7. Simulation results on impact of the residual dispersion slope at 160 Gb/s.

with the span launch power set to 5 dBm and 8.5 dBm respectively. At lower signal powers, for residual dispersion slope within ± 5 ps/nm^2 the additional penalty is very small. At higher signal powers, a residual dispersion slope within ± 5 ps/nm^2 gives an additional eye penalty of about 0.5 dB. It is also clearly visible that the penalty strongly increases when exceeding a certain limit. As a conclusion, dispersion slope is a limiting factor for 160 Gb/s transmission if no countermeasure is established.

In the practical fibers, both dispersion and dispersion slope values may vary randomly around an average value due to the manufacturing process. The random dispersion variation results in residual dispersion at the end of transmission, further modeling shows that this could lead to system performance penalty when the DCM is set to compensate the specified average dispersion due to the small dispersion tolerance window. Hence, additional dispersion compensation is required at the receiver when the dispersion variation is sufficiently large. However, the system has good tolerance to the dispersion slope variation, the impact of statistical dispersion slope variation on the system performance is very small.

3) Temporal Change of Chromatic Dispersion: To examine the evolution of the residual chromatic dispersion after the transmission link, RZ pulses of 2 ps FWHM from a mode-locked ERGO laser pulse source were coupled into a 275 km transmission link (described below in detail) and the pulse width of the received pulses after transmission was measured with the OSO. The results are shown in Fig. 8. During the

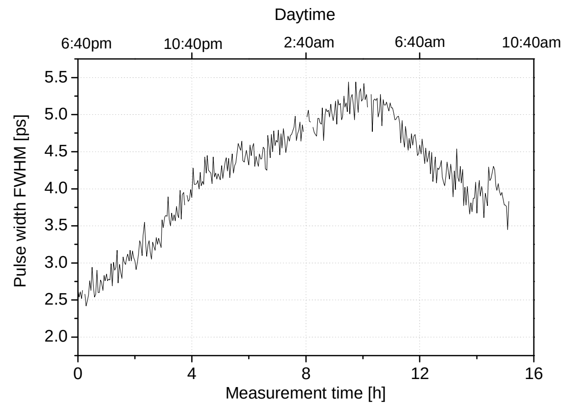

Fig. 8. Measured evolution of the pulsewidth after transmission over 275 km.

measurement the pulse width was recorded every 2.5 minutes. The pulsewidth varied from 2.5 ps to more than 5 ps FWHM. The latter number is much too high for 160 Gb/s transmission, where each bit slot has a duration of only 6.25 ps. As a consequence, tunable dispersion compensation is mandatory for 160 Gb/s systems.

4) PMD Tolerance and Compensation: As polarization mode dispersion (PMD) is a statistical effect, actual differential group delay (DGD) values can be much higher than the PMD value, which is an average number. Therefore the only way to specify system tolerance is to give outage probabilities, as every given DGD value can be exceeded with a given probability. Nevertheless, as a rule of thumb it can be said that a transmission system can stand a PMD value of about 10% of the time of a bit slot without any counter measure, resulting in 0.6 ps for a data rate of 160 Gb/s.

Since no commercial solution for PMD compensators at a data rate of 160 Gb/s is available today we have chosen a scheme based on the coupling into the principle state of polarization (PSP) of the transmission line [16] (see Fig. 9). To achieve PSP coupling a polarization controller has been installed at the beginning of the transmission link. At the end of the transmission line the degree of polarization was measured with the help of a PBS placed after a second polarization controller. The polarization controller was adjusted to minimize the depolarization at the output of the transmission line by minimizing the photodiode signal at the control output of the PBS. This method requires a back channel to provide information about the degree of polarization at the end of the transmission line to the polarization controller at the beginning of the transmission line. In the field trial this was realized by a back-to-back cable between transmitter and receiver located in the same room. In a real transmission system, for example overhead bits (for example in the SDH frame) in counter propagating data channels could be used for this purpose. For the networking experiments two independent PSP setups have been applied: first, between the transmitter and the TD-ADM, and second, between the TD-ADM and the receiver.

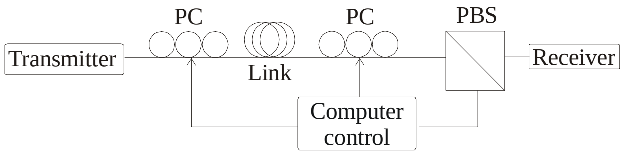

Fig. 9. PSP coupling scheme in the field trial.

Since the PSP coupling can only compensate for first order PMD we also performed simulations to qualitatively investigate the influence of higher order PMD on the transmission of 160 Gb/s signals. Signals were coupled into one PSP of a transmission fiber with a PMD value of 2.5 ps. Eye patterns were recorded after the PBS as used in the field trial. Figure 10 shows three different eye diagrams recorded with the same simulation setup but at different times. It can be clearly seen

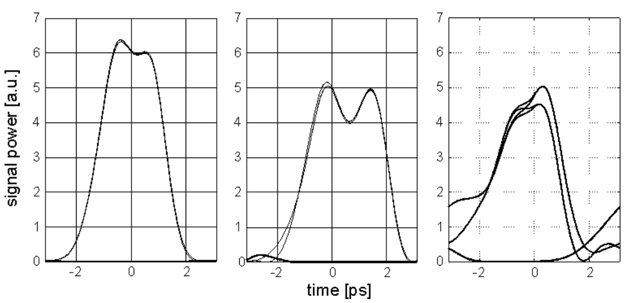

Fig. 10. Three eye diagrams simulated with the same setup show the impact of higher order PMD at different times.

that higher order PMD has a significant impact on the eye quality. As PMD varies over time, also the quality of pulses affected by higher order PMD is time dependent.

5) Polarization Management: The receiver and switching technologies used throughout the field experiments are polarization sensitive. To obtain the optimum polarization for the receiver and the switch manual PCs have been applied. For the PSP coupling scheme computer controlled PCs have been used. At the output of the PSP control a constant state of polarization was obtained. In case of the GT-UNI switch, the input polarization must be properly set to have an optimum τ_s. To cope with variation of the polarization states in the transmission fiber, it is desirable to use an automatic PCs at the input. Other PCs can be manually controlled because they do not require continuous adjustment once they are set to an optimum setting relative to the input polarization. This is also valid to the receiver. Minor adaptation were necessary occasionally due to a slow variation of the ambient conditions.

III. FIELD EXPERIMENTS

The OTDM signal of the transmitter was sent over SSMF fiber spans deployed between the UK towns of Ipswich and Newmarket, giving a span length of 68.85 km. The fiber has been buried in the ground for more than five years and their measured parameters are shown in Table I. The major equipments, like transmitter, receiver, and TD-ADM were placed in Ipswich. In Newmarket EDFAs and DCMs were installed. All equipments were placed in a standard exchange room without any climate control, which gave rise to a temperature variation of more than 10°C over the course of the day. Launch powers into the transmission fibers and the DCM were 8 dBm and 6 dBm, respectively. It should be mentioned that for the first DCM after the amplifier high order mode fiber was used to decrease the impact of nonlinearity. Chromatic dispersion was compensated after each span for about 70 km of SSMF. Residual dispersion at the end of the entire link or at the TD-ADM was adjusted for 100% compensation. Since the granularity of the DCMs on hand was 170 ps/nm and therefore two orders of magnitude higher than the necessary tolerance, additional fine-tuning was implemented by a set of SSMF with a granularity down to 10 meters inserted directly after the deployed fiber. As already shown in Figs. 6 and 7, careful dispersion slope compensation is also essential. We went for 100% slope compensation by combining two types of DCM, one designed for SSMF, the other for nonzero dispersion shifted fiber. The former undercompensates, the latter overcompensates the dispersion slope when used with SSMF. A PSP coupling scheme was applied to compensate for the first order PMD, as described above.

TABLE I

FIBER PARAMETER FOR THE TOTAL LENGTH OF 68.85 KM PER FIBER

Span no.	Loss dB	CD ps/nm	PMD ps	Span no.	Loss dB	CD ps/nm	PMD ps
1	15.3	1156	0.74	5	16.2	1165	1.00
2	16.8	1159	0.51	6	16.6	1159	0.71
3	16.7	1162	0.66	7	15.6	1160	1.20
4	16.5	1159	0.52	8	16.9	1149	2.60

A. OTDM Point-to-Point transmission

The field transmission experimental setup is shown in Fig. 11. The 160 Gb/s OTDM signal was sent via the PSP polarization control into transmission span #1 to Newmarket. After passing an EDFA, a DCM compensating for 70 km of SSMF and a further EDFA it was sent back via span #2 to Ipswich. Depending on the number of spans this was repeated two or four times. As a reference for the following results, sensitivity measurements in a B2B configuration have been conducted. The 160 Gb/s signal was taken directly from the transmitter and coupled into the demultiplexer. In the case of demultiplexing with FWM in SOA the clock was taken directly from the synthesizer (B2B clock). For the GT-UNI the CR was also used for the B2B BER evaluation. The resulting BER curves are shown in Fig. 14a) and c). We found sensitivities of about -24 dBm with FWM in SOA and -32 dBm with the GT-UNI for a BER of 10^{-9}. This difference of 8 dB can be explained by the fact that a FWM product is inherently of low power (< -20 dBm) and a substantial amount of optical signal to noise ratio (OSNR) is lost by the demultiplexing process. In the GT-UNI, the power levels of the signal never drop to such small values. Therefore, the loss of OSNR is less pronounced. The average penalties due to multiplexing and demultiplexing are estimated to be 6.7 dB for the GT-UNI switch.

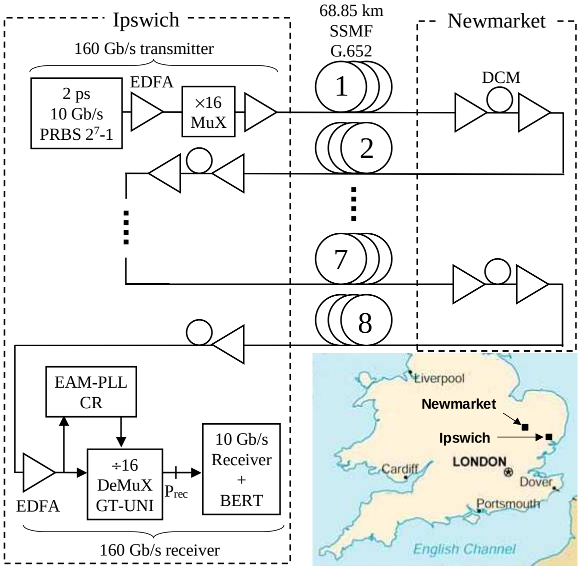

Fig. 11. Field trial point-to-point transmission setup connecting the telephone exchanges of Ipswich and Newmarket.

The spread in the sensitivity for the different channels for the back to back measurements was found to be 3.3 dB for the GT-UNI and about 4 dB for FWM in SOA. We ascribe these spread mainly to fluctuations in the multiplexer alignment due to temperature changes. For the transmission experiments additional spreading can be explained by changes of the residual chromatic dispersion. Since a reconfiguring of the fine-tuning fiber would have been necessary an adaptation of the chromatic dispersion during the measurement was not possible.

1) 137.7 km Transmission (Spans #1 and #2): After 137.7 km of transmission the median sensitivity for a BER of 10^{-9} is -31 dBm (GT-UNI) and -23 dBm (FWM in SOA). This gives a consistent penalty of 1 dB for both demultiplexing techniques introduced by 137.7 km of transmission. The corresponding BER curves are depicted in Fig. 12a and d.

2) 275.4 km Transmission (Spans #1 to #4): After 275.4 km of transmission the median sensitivity for a BER of 10^{-9} is -30 dBm (GT-UNI) and -22 dBm (FWM in SOA). This gives a consistent penalty of 2 dB for both demultiplexing techniques introduced by 275.4 km of transmission. When compared to 137.7 km of transmission one can see that the penalty increased approximately by the same amount than from B2B to 2 spans. The BER curves for 4 spans of transmission are depicted in Fig. 12b (GT-UNI) and Fig. 12e (FWM in SOA). In addition, an eye pattern diagram is shown in Fig. 12f.

3) 550.8 km Transmission (Spans #1 to #8): Experimental results of transmission over eight spans show that this distance is at the border of what is possible with the equipment used. The experiment was performed twice with quite unequal results. During the first measurement a BER value less than 10^{-9} was reached for the three measured adjacent channels. To be exact, BER values of 3.5×10^{-10}, 3.0×10^{-10}, and even 6.9×10^{-11} have been reached. Obtaining a BER value of

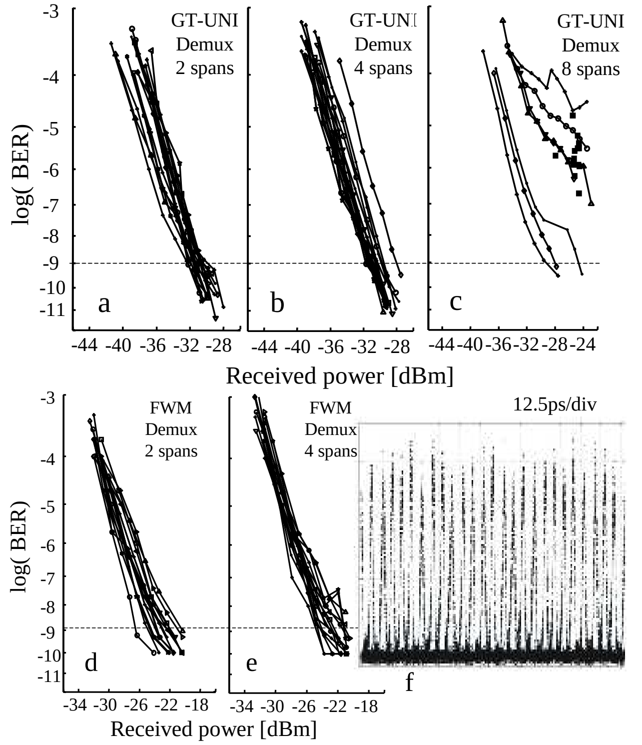

Fig. 12. (a), (b), and (c) show the BER curves measured with the GT-UNI for 2, 4, and 8 spans, respectively. (d) and (e) show the BER curves for FWM-SOA for 2 and 4 spans. (f) shows an eye diagram of the 160 Gb/s signal after transmission over 4 spans.

4.2×10^{-9} for the fourth channel without having adjusted the channel properly the experimentalists decided to proceed with the measurements next day. As it turned out, the performance reached the night before could not be repeated again for a period sufficient to perform sensitivity measurement. Though BERs in the order of 10^{-9} could be measured again, but only for some tens of seconds, not long enough to execute reliable measurements. We ascribe these long term fluctuations in the performance mainly to the statistical impact of higher order PMD, for which no compensation was possible during the course of the project. In addition, it turned out that the dispersion compensation had to be readjusted. Due to the very tight tolerances for the dispersion after 8 spans of transmission (see section II-E) the optimum configuration could not be achieved again. In the second measurement a BER of 10^{-7} was achieved. Some channels showed even worse performance. Due to the long measurement time necessary to take the sensitivity curves of all channels and the rather fast fluctuations of the transmission performance due to higher order PMD, we decided to take the BER of all channels at a fixed input power of about -25 dBm. For 4 adjacent channels the complete sensitivity curves were measured. It is visible that the single point measurements lay well in the range given by the full sensitivity measurements (Fig. 12c).

B. OTDM Networking

For OTDM networking experiments spans #1 to #4 were chosen. The setup and the eye patterns at different positions in the setup are shown in Fig. 13. The eye pattern is clearly

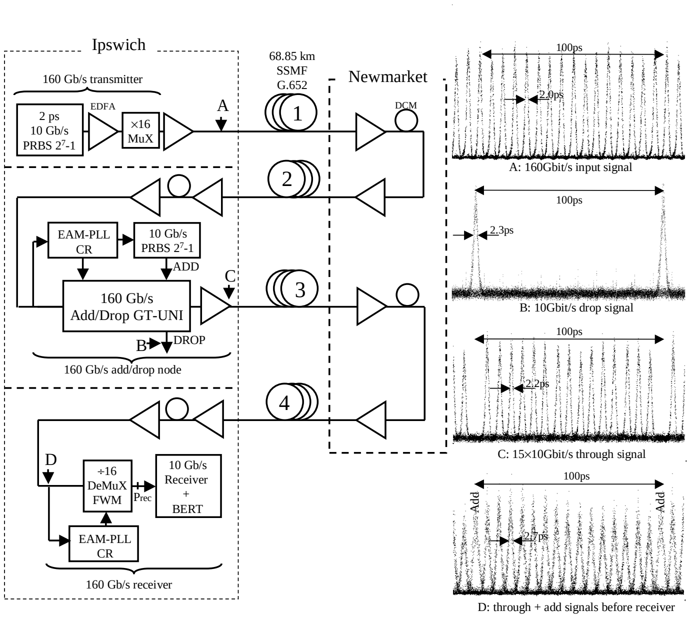

Fig. 13. Field trial OTDM networking covering transmission and switching functions. The eye patterns were taken at the positions indicated by A–D in the network.

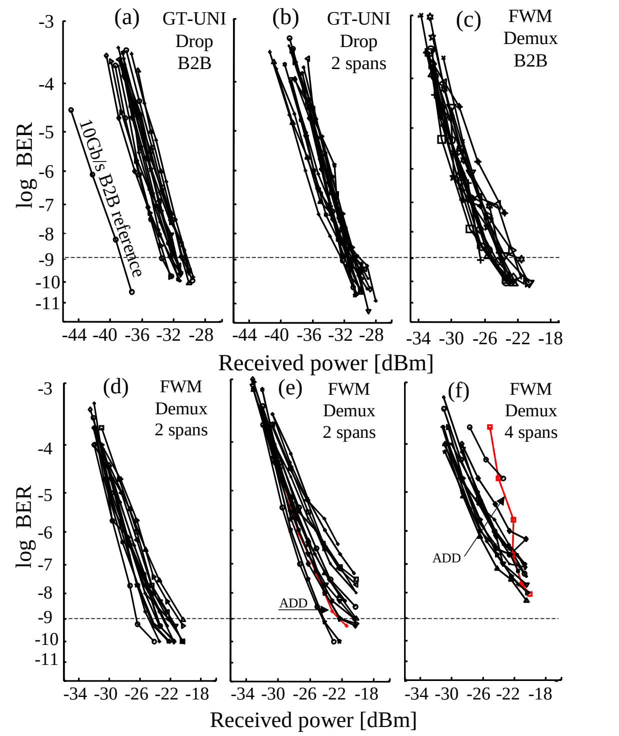

Fig. 14. BER performance of switching function: (a) B2B, (b) drop after 2 spans, (c) B2B FWM, (d) before TD-ADM, (e) after TD-ADM for through and add function, and (f) after additional 2 spans.

open for all channels and good drop and through operation is visible. The pulse width evolves from 2.0 ps at the transmitter output, to 2.2 ps in the through port after the TD-ADM, and 2.7 ps before the OTDM receiver. From all eye diagrams it can be seen that the pulse shape and quality are well preserved during transmission and switching. Minor amplitude variation of the through channels due to the residual gain changes in the GT-SOA can be observed. Two identical CR subsystems have been built. One CR is attached to the TD-ADM and the other to the pulse source of FWM in SOA. The EAM in the second CR for FWM in SOA is not impedance matched and therefore the jitter performance is more than 600 fs. The CR for the TD-ADM has less than 250 fs time jitter. Figure 14 shows BER curves of the transmission and switching function. We evaluated the demultiplexing performance using the drop function of the GT-UNI (Fig. 14a–b) and FWM in SOA (Fig. 14c–f). Figure 14b shows the BER values of all channels dropped by the GT-UNI after 2 spans (138 km). The B2B BER curve in Fig. 14c for demultiplexing by FWM in SOA is the reference for the following networking measurements. Figure 14d shows the BER results of FWM demultiplexing before the TD-ADM. The average sensitivity is observed to be -23.3 dBm. Directly after the TD-ADM the average sensitivity for the through and add channels is -20.7 dBm (Fig. 14e). This sensitivity value leads to a penalty of approximately 2.6 dB in the 160 Gb/s TD-ADM. This penalty is largely caused by OSNR degradation in the GT-UNI switch. After additional two spans the transmission (Fig. 14f) quality of the signal degraded, however it was significantly above the forward error-correction threshold for BER$< 10^{-12}$. This degradation is caused by the fact that the operational margins are very narrow for this transmission range. The time varying effects like higher order PMD started to become detrimental to the signal quality.

IV. Network Aspects

The typical change of the optical transmission time of a pulse through of a fiber with temperature change is 40 ps/(km·K) which causes drifts in the bit phase [17]. Such drifts, over a long time scale and an enormous number of bits as well as short variations over several bit slots, will have to be adapted in future meshed OTDM networks.

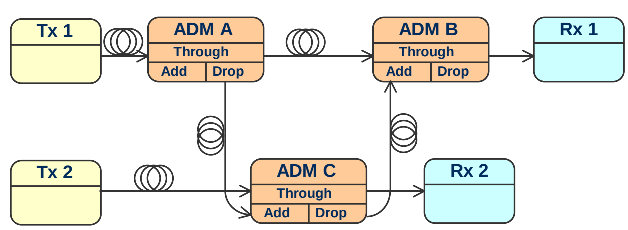

Fig. 15. Example of a meshed OTDM network with three TD-ADMs and two transmitter and receivers.

Figure 15 illustrates a small meshed OTDM network consisting of three network nodes ADM A, B, and C, with the following traffic flows:

Tx1	→	ADM A	→	ADM B	→	Rx1
Tx1	→	ADM A	→	ADM C	→	Rx2
Tx2	→	ADM C	→	ADM B	→	Rx1
Tx1	→	ADM C	→	Rx2		

In order to avoid collision in the TD-ADMs a phase control has to be implemented at the inputs of the TD-ADM controlled by a suitable monitoring system. In the concept illustrated in Fig. 16 one or both of the input signals pass through a variable delay before entering the intrinsic TD-ADM. The delay line can be realized, for example with free space optics, fiber wound around a piezo or heated fiber. For very large phase shifts phase controllers with large possible delays have to be developed. First concepts are under consideration and seem to be promising. The controller of the variable delay system is fed by a time-slot monitor placed at the output of the TD-ADM. With help of this concept phase drifts of the different data streams relative to each other are compensated.

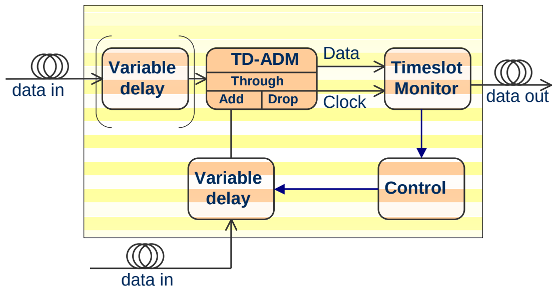

Fig. 16. Schematic layout for an TD-ADM for a meshed network. The phase of one or both (not shown) incoming data signals can be controlled by a variable delay before entering the intrinsic TD-ADM. The temporal change is recorded by a time slot monitor giving a measure for the delay control.

In order to be able to merge two completely arbitrary data streams to a single data stream an enhanced node architecture is necessary. In Fig. 17 a layout of the TD-ADM node is presented with which two OTDM data streams can be merged to a single OTDM data stream without collision of the data channels. With this concept a total number of up to 16 OTDM channels can be handled. In general, for a TD-ADM combining node as described above to merge two data streams S1 and S2 with a maximum number of OTDM channels of N, $N/4$ single TD-ADMs and $(N/4)+1$ delay lines are required.

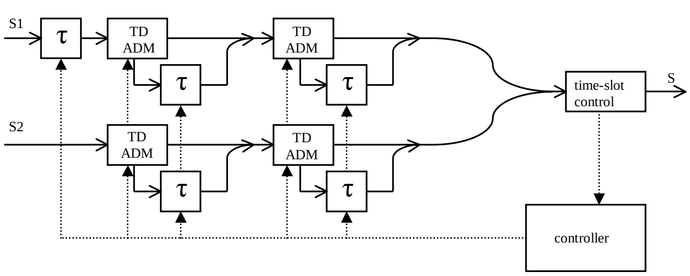

Fig. 17. Possible layout for the combination of two OTDM signals which is capable to reorder the single OTDM channels up to a total number of 16 channels.

Before entering the TD-OADM a detector (not shown in Fig. 17) unit determines the occupied channels of both incoming data streams S1 and S2. Information about the occupied and free bit slots of the data streams are used to set the 5 delay lines and choose up to 2 channels per incoming data stream for which a different bit slot is necessary to avoid collision at the combiner. In order to have a sufficient fine tuning in the channel separation a time-slot control after the combiner of the two incoming data streams is used. At each TD-ADM one channel of the time domain signal can be dropped, delayed and added in a bit slot suitable to obtain a collision free combined signal. In Fig. 18 two examples are given how this rearrangement of the two data streams can be performed.

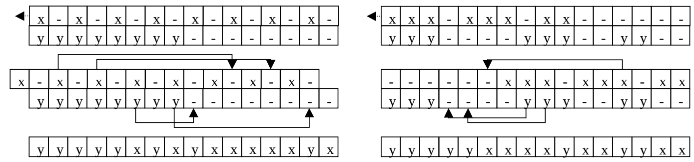

Fig. 18. Two examples for the rearrangement with the concept presented. The occupation of the time slots of the two incoming signals are shown. An X or Y in a time slot shows that the corresponding timeslot of the incoming signal S1 or S2 is occupied, respectively. In a first step one of the incoming data streams is delayed in such way that a minimum of overlapping bits is present (top graph). The remaining overlaps were dropped, delayed and added at the suitable free bit slot (middle graph) and form a collision free OTDM signal (lowest graph).

V. Conclusions

A fully functional 160 Gb/s OTDM add-drop network constructed with the field deployed fiber network of the British Telecom has been presented. We have shown error free transmission of 160 Gb/s signals over 137 and 275 km of deployed SSMF with small power penalties compared to back to back performance. A gain transparent ultrafast nonlinear interferometer was inserted in these links to demonstrate OTDM networking. All network functionalities, i.e. transmission, clock recovery, and switching showed good performance. In addition, transmission results over 550 km legacy fiber has been demonstrated with quite different results, which suggest that this distance is the edge of technical feasibility. This is in good agreement to the numeric simulation results. Further enhancement of the network performance and stability requires automatic dispersion and PMD control. Moreover, compact and robust OTDM subsystems such as transmitters, clock recovery, add-drop multiplexers, and the demultiplexers are highly required to improve the performance stability. The result proves that OTDM add-drop functions in the existing fiber networks are feasible. All necessary key components are available and experimentally tested.

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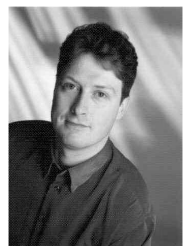

Gottfried Lehmann was born in Freiburg, Germany, in 1970. He studied physics at the Universities of Freiburg and Heidelberg, Germany. After receiving his Ph.D. from the University of Heidelberg in 2001 in the field of ultrasonic and super-hard material, he joined Siemens AG, Information and Communication Networks, where he was working in the Advanced Transport System department. Here he was investigating the physical limitations of optical transport systems. In February 2003, he changed to the Information and Communication department of Siemens Corporate Technology and took the project management of the FASHION 160 Gb/s project. He authored or co-authored about 20 scientific publications.

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Wolfgang Schairer was born in Ulm, Germany, in 1973. He studied physics at the Ludwig Maximilians Universität (LMU) in Munich and received his diploma in 2001. His diploma theses was on the topic of photoinduced THz-absorption in disordered semiconductors. When he joined Siemens AG, Information and Communication Networks, he worked on doubling transmission fiber capacity by polarization multiplexing. In February 2003, he changed to the Information and Communication department of Siemens Corporate Technology.

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Ed Sikora started his career at BT in 1989, following a move from The GEC Hirst Research Centre. He has carried out studies and led work in a number of different areas of optical fibre transmission, optical network design and system evaluation, fibre reliability and impairments such as loss due to hydrogen and PMD. His present work ranges from high optical power damage to fibres, the transmission and techno-economic studies of ultra high speed TDM transmission technologies, developing optical fibre sensors for use in optical transmission networks, network performance and security, the evaluation of new optical switching and management systems and subsystems, , and providing the technical input to future fibre specs for BT.

Andrew Lord graduated from Oxford University in 1985 having read Physics. Since joining BT, he has worked on many aspects of optical transmission as it has developed from early regenerated 565 Mb/s systems right through to current research at 160 Gb/s. His work has included detailed modelling of transmission effects including optical amplifiers, optical noise, polarization and chromatic dispersion, effects of different fiber types, different modulation formats, and the nonlinear effects of DWDM. He has been actively involved in the transmission issues of subsea systems such as TAT14 as well as providing transmission and fibre expertise for BT's core network. Current activities range from EU collaborative work on photonic networks to fibre-to-the-home research.

Dave Payne has worked in optical technology and networks for the past 20 years. He started at BT Laboratories, Martlesham Heath, on single-mode fibre-splicing and connectors, and was instrumental in moving single-mode fibre transmission systems to practical reality in early 1980s. He then move on to optical networking, exploiting single-mode fibre technologies. This included development of fused fibre couplers and using them in passive optical networks. By the mid-1980s, he was involved in the early design and experiments with wavelength switching and routing networks; his early work led him and his colleagues to invent TPON (telephony over passive optical network) concept which was further developed in the latter part of the 1980s. During the early 1990s, he was further involved with various optical network designs and experiments including the application of WDM technology to the access and metro environments. This culminated in an experiment in 1991 involving a 44 milion-way split amplified optical network with a reach of over 500 km carring 16 wavelengths at 2.5 Gbit/s each. The use of amplifiers led to the SuperPON idea (passive optical networks employing amplifiers) to further reduce costs for FTTH systems. In the last few years he has moved into the core transport area and has been involved in business and traffic modelling looking at the drivers of bandwidth that could lead to the economic justification for large scale deployment of optical networks. He now runs the Broadband Architectures and Optical Networks Unit at BT Adastral Park, Martlesham Heath, covering both core and access networks.

Giok-Djan Khoe was born in Magelang, Indonesia, in July 1946. He received the degree of Elektrotechnisch Ingenieur, cum laude, from the Eindhoven University of Technology TU/e, Eindhoven, The Netherlands, in 1971 and began his research career at the Dutch Foundation for Fundamental Research on Matter (FOM) Laboratory on Plasma Physics, Rijnhuizen. In 1973 he moved to the Philips Research Laboratories working in the area of optical fiber communication systems. In 1983 he was appointed as part time professor at TU/e, became a full professor in 1994 and is currently chairman of the Department of Telecommunication Technology and Electromagnetics (TTE). Most of his work has been devoted to single-mode fiber systems and components. Currently his research programs are centred on ultrafast all-optical signal processing, high capacity transport systems and systems in the environment of the users. He has more than 40 United States Patents and has authored and co-authored more than 100 papers, invited papers and chapters in books. He was general co-chair of ECOC 2001 and was a founder of the LEOS Benelux Chapter. Currently, he is associate editor of IEEE J. Quantum Electronics. He has been an IEEE Fellow since 1991 and received the MOC/GRIN award in 1997. In 2003 he was appointed President of LEOS.

Huug de Waardt was born in Voorburg, The Netherlands, in December 1953. He received the M.Sc.E.E. and the PhD degrees in 1980 and 1995 respectively from the Delft University of Technology, The Netherlands. In 1981 he started his professional carrier in the Physics Department at PTT Research in Leidschendam, The Netherlands where he worked on the performance issues of semiconductor laser devices. In 1989 he moved to the Transmission Department and became involved in high bit-rate optical transmission. In 1995 he was appointed as associated professor at the TU/e-E in the area of high bit-rate trunk transmission. He coordinated the participation of TU/e in ACTS Upgrade, ACTS BLISS, ACTS APEX, and IST FASHION. His current research interests are in high capacity optical transmission, integrated optics and semiconductor optical amplifiers. He (co)authored over 75 scientific contributions. He is member of the IEEE Laser and Electro-Optics Society.