All-Semiconductor 1310-nm 90-Gbit/s WDM Transmission for LAN/MAN Applications
J.P. Turkiewicz, E. Tangdiongga, G.D. Khoe, H. de Waardt
COBRA Research Institute, Eindhoven University of Technology,
P.O. Box 513, NL-5600 MB, Eindhoven, The Netherlands (j.turkiewicz@tue.nl)

Abstract We demonstrate successful multi-Gbit/s 1310-nm WDM transmissions with variable bitrates and modulation schemes using SOAs. An aggregate capacity of 90 Gbit/s is transmitted over 90-km standard fibers. An averaged 17.5dB Q-factor (BER<10^{-12}) for all channels is achieved.

Introduction
Optical communication systems operating at multi-Gbit/s, such as 10-Gigabit Ethernet are becoming increasingly important in local area networks (LANs) and metropolitan area networks (MANs) [1]. For such networks of medium distances, the installed fiber-based infrastructures operated at 1310 nm offer a serious alternative for realizing low-cost and high-capacity Ethernet systems, alleviating any need for dispersion compensation. A first successful 1310-nm 4x10-Gbit/s WDM transmission over 80 km employing semiconductor optical amplifiers (SOAs) was demonstrated by [2].

In this paper, we significantly improve the performance of the WDM system in [2] by increasing the transmission reach, the bandwidth efficiency, and the system capability to transmit/receive WDM signals of different bitrates and modulation schemes. To our knowledge, this work presents the first demonstration of WDM systems with variable transmission schemes using commercially available 1310-nm devices. We have reached a transmission record of 90 Gbit/s, comprising four channels at 20 Gbit/s each and one channel of 10 Gbit/s. Sufficient optical signal-to-noise ratio (OSNR) of more than 21dB and Q-factors of better than 17.5dB were obtained after transmission over approximately 90 km standard single-mode fiber (SMF). We believe that this result proves the feasibility of 1310-nm multi-gigabit Ethernet systems using the installed fiber-based infrastructures.

Experimental setup
We performed two different modulation schemes in the experimental setup in Fig. 1. Four low-cost DFB laser diodes (two Mitsubishi FU-445SDF and two Lucent Technologies D-372) operating in CW conditions form the input of a 20-Gbit/s external modulator (Sumitomo T.MZI.3-20). The laser diodes are provided with external Peltier-coolers to accommodate wavelength tuning. The wavelength spacings are 150, 250, and 200 GHz. These unequal channel spacings are chosen as such that four-wave mixing is sufficiently suppressed [3]. We used a signal generator (SHF) to make 20-Gbit/s data streams. The 20-Gbit/s WDM signals are simultaneously amplified by a single SOA booster (JDS-Uniphase CQF881) to compensate for losses of the 4-to-1 optical combiner (6.5dB) and the external modulator (7.6dB). Dispersion-shifted fiber (D=+17 ps/km/nm) of 5 km is located after the SOA booster (SOA#1) to decorrelate the bit-patterns.

An additional laser source (Agere D1816A) operating at 1315.84 nm is directly modulated by a 10-Gbit/s HP generator. This signal is inserted to the transmission fiber by a 50/50 coupler. The data formats are 2^{11}-1 NRZ PRBS. The composite 90-Gbit/s signal is sent to two SMF spans (38 and 51 km) with an in-line SOA#2 between them. Before reaching the receiver section, the WDM signals are amplified and subsequently split in two paths. One path is designed to receive only the 10-Gbit/s data streams and the other to receive one of the 20-Gbit/s channels. Three optical band-pass filters (BPFs) in the receiver scheme carry out channel selection and noise suppression, see Fig. 1. For the 20-Gbit/s channels we used an optically preamplified receiver scheme, i.e. SOA#4 followed by an optical BPF, as the 30-GHz opto-electrical (O/E) converter has a considerably less sensitivity compared to the sensitivity of the 10-Gbit/s optical receiver circuit (NEL MOS42AM).

Results and Discussions
Fig. 2 shows the WDM spectra taken by an optical spectrum analyser at the point before and after the
90-km transmission. All SOAs in this experiment are driven close to their saturation condition in order to optimize the output signals for highest OSNRs and lowest WDM crosstalk [4].

![Fig. 2: Transmitted and received spectra. OSNRs are better than 21dB. No FWM is observed.](image)

There is less than 1-dB power tilt between the longest and shortest wavelength channel because the channels are located slightly in the red side (longer wavelengths) of the gain peak. The channel OSNRs decrease considerably from 36dB to 21dB due mainly to accumulated amplifier noise. No four-wave mixing in the SOAs and the transmission fiber is observed in this experiment. The WDM channel performance is evaluated by looking at the Q-factor of each channel for an identical power level. The back-to-back (B2B) performance is measured by directly connecting the transmitter to the receiver section. The results are listed in Table 1.

<table>
<thead>
<tr>
<th>Channel #</th>
<th>B2B [dB]</th>
<th>System [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.3</td>
<td>18.1</td>
</tr>
<tr>
<td>2</td>
<td>19.2</td>
<td>17.8</td>
</tr>
<tr>
<td>3</td>
<td>19.0</td>
<td>17.6</td>
</tr>
<tr>
<td>4</td>
<td>19.1</td>
<td>17.5</td>
</tr>
<tr>
<td>5</td>
<td>19.8</td>
<td>19.1</td>
</tr>
</tbody>
</table>

Table 1: Q-factor at -8dBm/channel after SOA#3

Also, Table 1 lists the Q-factor performance of the WDM system after transmission over 90-km SMF. The average Q-factor is 17.8dB of which the worst channel is 17.5dB. Roughly speaking, all channels experienced Q-factor degradation due largely to the beating of the signal with accumulated ASE noise and the residual cross-gain modulation in the SOAs. We can clearly see in Table 1 that the 10-Gbit/s signal is less degraded (0.7dB) than the 20-Gbit/s signals (1.4dB averaged). This might be caused by higher WDM crosstalk penalties in the SOAs experienced by the 20-Gbit/s channels than the 10-Gbit/s channel. The 10-Gbit/s channel exhibits the SOA highest saturation output power. The same phenomena we see reflected within Fig. 3, representing the eye patterns of the mid-channel 3 (λ=1310.61nm) before and after 90-km fiber transmission. The eye diagrams look identically, showing that no significant distortion in the signal shape is observed in the proposed WDM transmission, especially in the center of the eyes.

![Fig. 3: Eye diagram of Ch3 carrying 20 Gbit/s NRZ PRBS data: (a) before and (b) after 90-km SMF.](image)

For feasibility studies of 8×20-Gbit/s WDM systems or higher, the setup was modified slightly by increasing the optical power of the 10-Gbit/s channel by a factor of 8dB. This power increase emulates at least four additional WDM channels. We have observed that all four 20-Gbit/s channels have at least 17.3dB Q-factor, which is theoretically still sufficient to reach BER=10^-12. This excellent performance indicates that the 1310-nm WDM system for LAN/MAN spans can be extended to have more than eight 20-Gbit/s wavelength channels with an aggregate capacity of 160 Gbit/s.

Conclusions
We have demonstrated dense WDM transmission of 90 Gbit/s data (4×20 Gbit/s external and 1×10Gbit/s direct modulation) over 90 km standard fiber, which is to our knowledge, the highest composite bitrate and also the longest distance bridged to date in WDM 1310-nm transmission using conventional SOAs. Minimum Q-factor of 17.5dB (corresponding to BER lower than 10^-13) was obtained for all channels. This result shows unequivocally that SOA-based 1310-nm WDM transmission systems over the installed fiber-based infrastructures offer a viable solution for multi-Gbit/s Ethernet in LAN and MAN spans.

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References
1. Cunningham ECOC2001 Invited Paper We.B.3.5.