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Static and Dynamic Switching Performance of a Metro WDM Ring Using Linear Optical Amplifiers

J. J. J. Crijns, L. H. Spiekman, G. N. van den Hoven, E. Tangdiongga, and H. de Waardt

Abstract—The authors demonstrate the performance of a dynamic and reconfigurable metro-size wavelength-division-multiplexing (WDM) ring employing eight cascaded linear optical amplifiers. The ring has eight uncorrelated WDM channels, modulated at 10 Gb/s each. Measured Q-factor of all channels are between 17.6 and 18.7 dB, corresponding to a bit-error rate of less than $2 \times 10^{-14}$. In an add/drop experiment, dynamic switching of channels does not affect transmission quality of the through channels.

Index Terms—EDFA, gain dynamics, metropolitan networks, optical amplification, wavelength-division multiplexing.

I. INTRODUCTION

It has become clear in recent years that the part of the optical network that is close to the end-users must offer sufficient flexibility in order to allow upgrading by the network operator and sometimes even dynamic reconfigurability to allow cost-effective operation of the network. In addition, the components themselves have to be low cost since the cost is shared by a smaller number of network users. In this letter, we focus on the amplifiers in such a system. Semiconductor technology promises low-cost amplification, and the recently introduced linear optical amplifier (LOA) [1] solves the problem of wavelength-division-multiplexing (WDM) crosstalk between channels that has previously been a major performance limitation in semiconductor devices [2]. Using eight cascaded LOAs, a metro-size WDM ring of 200-km length employing three add/drop nodes has been built. System performance of both static adding and dropping of channels, as well as dynamic switching in and out of wavelengths, is experimentally evaluated.

II. NETWORK CONCEPT

A diagram of the metro-size WDM ring network is shown in Fig. 1. Eight wavelengths (1551 to 1557 nm, spaced 100 GHz) are sourced at the point-of-presence (PoP), where the ring can be coupled to the backbone. All WDM channels are non-return-to-zero (NRZ)-modulated electrically at a data speed of 10 Gb/s using a pseudorandom bit sequence (PRBS) generator of a repetitive length $2^{24} - 1$. After modulation, the WDM channels are decorrelated using 10 km of standard single mode fiber (SSMF). The eight channels are amplified to a total optical power of approximately 6 dBm by a booster LOA and then launched into the transmission fiber.

The signals traverse fiber spans of 50, 60, 50, and 40 km SSMF, encountering add/drop nodes along the way. Each node contains a fiber Bragg grating (FBG) and an optical circulator by which a fixed channel at $\lambda_0$ can be dropped from the ring. The through channels are coupled to a dispersion compensating fiber (DCF) which is designed to nominally compensate dispersion of 50-km SSMF. Subsequently, a 50/50 optical coupler is inserted in the node, enabling us to add a channel into the ring. Two LOAs per node, each located at the input and output, are for compensating both the span loss and the node loss of about 12 dB each. The net gain in each node is approximately equal to the span loss. After the last fiber span, an LOA-preamplified receiver in PoP terminates the ring.

The LOAs used in this experiment are MOCVD-grown InP-based semiconductor devices that integrate an active waveguide and a vertical cavity surface emitting laser (VCSEL) on the same chip [1]. The VCSEL has been elongated to coincide with the active waveguide along its entire length. This way, the active region of the device is shared among the VCSEL and amplifier.
The VCSEL lasing action clamps the gain everywhere in the waveguide, avoiding intersymbol interference and multichannel crosstalk that impede WDM operation in traditional semiconductor optical amplifiers (SOAs). Typical gain of the LOAs used in the experiment is 12 dB with a polarization dependence of <1 dB. Noise figures are around 8 dB, and the LOAs are operated at (average) output powers up to +6 dBm.

III. EXPERIMENT

Transmission performance of the ring has been determined by evaluating the $Q$-factor of a 10-Gb/s receiver, as described in [3]. The results are plotted in Fig. 2. Out of the eight channels launched in PoP, channel $\chi_3$ is dropped by the FBG in node 1, channel $\chi_5$ is dropped in node 2, and channel $\chi_7$ in node 3. Channel $\chi_1$ and the even channels travel all the way around the ring back to the PoP. Transmission performance is mainly determined by noise accumulation, with the worst performing channel (channel $\chi_1$) achieving a bit-error rate (BER) of $2 \times 10^{-14}$ after 200-km SSMF and eight cascaded linear optical amplifiers. The OSNR for this channel is 21 dB, as seen in the optical spectrum after the preamplifier at the far end of the ring (see Fig. 3). Three out of eight channels have been dropped, together with the amplified spontaneous emission (ASE) in the bandwidth of the FBGs that was accumulated up to the drop point. Comparison with all eight channels straight through to the receiver (by removing the FBG’s from the nodes) shows very little difference both in the OSNRs and in the relative powers of the channels, owing to the good linearity of the optical amplifiers. The natural gain flatness of the amplifiers causes a maximum received power imbalance of 1.2 dB (with the transmitter equalized to <0.1 dB) without any flattening mechanisms. We want to remark here that channels $\chi_5$ and $\chi_7$ do not match perfectly with the passband of the FBG in nodes 2 and 3, causing the observable residual spectra of those channels in Fig. 3.

Fig. 4 shows the consequences of a channel being added at node 1 by injecting an optical signal at the wavelength of channel $\chi_3$ in the 50/50 coupler. The performance of the other channels ($Q$-factors shown for $\chi_2$ and $\chi_4$) depends very little on the presence or absence of this channel.

IV. DYNAMIC SWITCHING OF CHANNELS

Stronger evidence on the insensitivity of the transmission line to power transients can be obtained by switching not one but four channels ON and OFF, simulating dynamic adding and dropping of many wavelengths [4]. To this end, channels $\chi_2$, $\chi_4$, $\chi_6$, and $\chi_8$ were lead through an acoustooptic modulator (AOM) before being modulated at PoP. This way, half of the power being launched could be switched ON and OFF dynamically.

In Fig. 5, eye diagrams are presented of channel $\chi_3$, in which its original data stream was dropped and a new data stream was added at node 1. The eyes were taken at the end of the transmission line, after the preamplifier, using a broad-band OE converter and a 30-GHz digital communication analyzer. From left to right, eyes are shown for only the odd channels present in the system, for all eight channels present, and for the dynamic switching situation in which the even channels

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**Fig. 2.** Performance of each channel expressed in $Q$-factors. Channels $\chi_3$, $\chi_5$, and $\chi_7$ are evaluated at the node where they are dropped from the ring. Other channels are evaluated at PoP after traveling 200 km and 8 LOAs. $\triangle$: Dropped channel, $\diamond$: Through channel.

**Fig. 3.** Spectrum of the WDM channels at the receiving side of PoP. Two spectra are shown: all channels are present (dashed curves) and channels $\chi_3$, $\chi_5$, and $\chi_7$ are dropped (solid curves). Resolution bandwidth is 0.1 nm.

**Fig. 4.** $Q$-factor performance of channel $\chi_3$, which is added at node 1 and its adjacent channels. Switching ON/OFF channel $\chi_3$ has very little impact (0.1–0.2 dB) to the adjacent channels, demonstrating the insensitivity of the amplifiers to varying total power. $\diamond$: Channel $\chi_3$ OFF; $\Box$: Channel $\chi_3$ ON.
were switched ON/OFF with a frequency of 1 kHz. This low switching speed is of the same order with the switching speeds of wavelength-switched optical networks, such as silicon-based microelectromechanical systems (MEMS) [5]. The slight difference in amplitude of the eye for the four-channel and the eight-channel situation reflects the residual gain compression of 0.5 dB after six cascaded amplifiers. The difference between eight channels and the dynamically switched situation is marginal. It should be noted in Fig. 5 that the peaking of the eyes is caused by 60-km undercompensation of fiber dispersion. For comparison, the same series of eyes has been taken after replacing the six LOAs in the nodes by three (nontransient-controlled) EDFAs (one EDFA per node). Since the EDFAs are operated in saturation, very different gains are obtained for the four-channel and the eight-channel case. In addition, due to the gain transients [6] having time-scales comparable to the switching speed, error-free reception in the switched case cannot be expected.

V. CONCLUSION

We have demonstrated an 8 × 10 Gb/s four-node metro-size WDM ring in which each add/drop node drops a fixed wavelength and allows a wavelength of a new data stream to be added. Only semiconductor-based amplifiers, LOAs, are being used, and the results show both the cascadibility of these devices and their excellent insensitivity to power fluctuations in the network. Transmission through 200 km of standard fiber and eight cascaded LOAs shows a worst channel Q-factor performance of 17.6 dB, corresponding to an error rate of 2 × 10⁻²⁴. In addition to the excellent Q-factor performance, dynamically switching ON/OFF four out of eight channels results in a power transient at the end of the transmission fiber of only 0.5 dB.

REFERENCES