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Citation for published version (APA):
Tangdiongga, E., Crijns, J. J. J., Spiekman, L. H., Hoven, van den, G. N., & Waardt, de, H. (2002). Performance analysis of linear optical amplifiers in dynamic WDM systems. *IEEE Photonics Technology Letters*, *14*(8), 1196-1198. https://doi.org/10.1109/LPT.2002.1022016

DOI:
10.1109/LPT.2002.1022016

Document status and date:
Published: 01/01/2002

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Performance Analysis of Linear Optical Amplifiers in Dynamic WDM Systems

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

***Abstract*—We demonstrate the performance of linear optical amplifiers (LOAs) in a dynamic and reconfigurable wavelength-division-multiplexing (WDM) system. Eight WDM channels, each channel running at 10 Gb/s, are transmitted through two cascaded LOAs. Power transient immune add-drop capability is demonstrated by switching four of the eight channels at rates of 10–100 kHz without affecting the bit-error-rate (BER) or eye pattern. The same WDM system trial using erbium-doped fiber amplifiers instead of LOAs shows identical BER performance for the eight-channel case, but deteriorated eye patterns and bit error penalties for the channel ADD–DROP configuration.**

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

I. Introduction

AMPLIFICATION in metro and access systems is becoming the enabling factor to meet the price/performance targets of next-generation optical networks [1]. New optical functions, such as channel adding and dropping, switching, and routing of signals, introduce loss in network nodes. An optical amplifier technology is required that enables faithful amplification of the signal, regardless of data rate and channel count, even under dynamic conditions. The linear optical amplifier (LOA) has been specifically designed to meet the requirements of next generation networks [2].

Being a single-chip, InP-based amplifier, it has size and cost advantages over conventional amplifier technologies. Unlike the semiconductor optical amplifier (SOA), which suffers from gain compression leading to crosstalk and distortions in optical systems [3], the LOA is linearized to enabling faithful amplification of the optical signal. Especially important for dynamic systems, the LOA gain is fixed, i.e., independent of the instantaneous input power, making it immune to power transients in the network.

In the previous work described in [2], major performance differences were notified between a LOA and an EDFA in terms of transient response on device level. In this letter, the performance of a WDM system with cascaded LOAs is assessed and compared to a system with Er-doped fiber amplifiers (EDFAs). The capability of amplifying multiple channels without interchannel crosstalk is shown, and for the first time power transient immune behavior is demonstrated in a LOA-based WDM system without any means of external transient control.

Manuscript received November 21, 2001; revised March 19, 2002.
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Publisher Item Identifier S 1041-1135(02)06264-X.

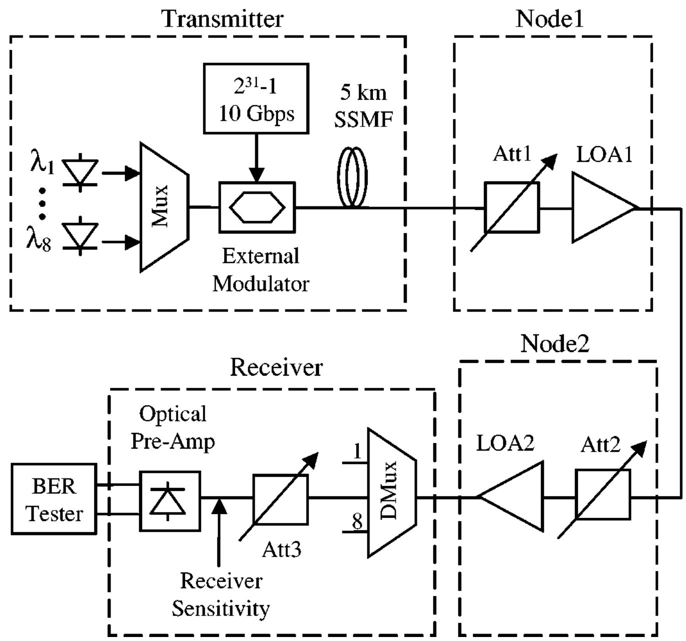

Fig. 1. Experimental setup of 8 × 10-Gb/s WDM system using linear optical amplifiers.

II. WDM System Trial

Fig. 1 shows schematically the experimental setup of a WDM system using LOAs. A detailed description of a packaged LOA module can be found in [1], [2]. To concentrate purely on the LOA performance in a multichannel environment, an optical system was built up with optical attenuators, simulating fiber, and node losses. The experimental setup has four optical nodes: one transmitter, two intermediate, and one receiver node. In each intermediate node, we used an optical variable attenuator $(\mathrm{Att1}, \ldots, \mathrm{Att3})$ to simulate optical losses caused by optical nodes. The transmitter node consisted of eight distributed feedback lasers that generated continuous-wave (CW) signals spaced at 200 GHz in the 1549.2–1560.6 nm range. The CW signals were multiplexed and modulated simultaneously at 10 Gb/s with a pseudorandom bit sequence (PRBS) of length $2^{31}-1$. The signals were coupled to 5 km (-80 ps/nm) of standard single-mode fiber (SSMF) to produce decorrelated bit patterns at the output of the transmitter node.

The modulated signals entered the first intermediate node (Node1) where they were attenuated by the first attenuator (Att1) and then boosted by the first LOA (LOA1) to a total

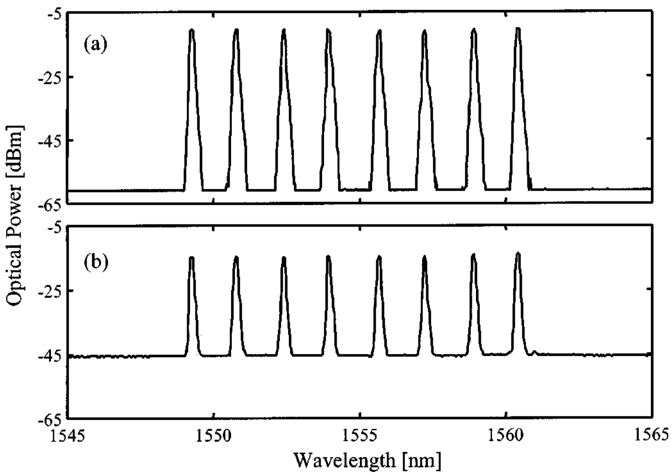

Fig. 2. Spectra of all eight WDM channels: (a) after the transmitter node. (b) before the receiver node. Resolution bandwidth is 0.1 nm.

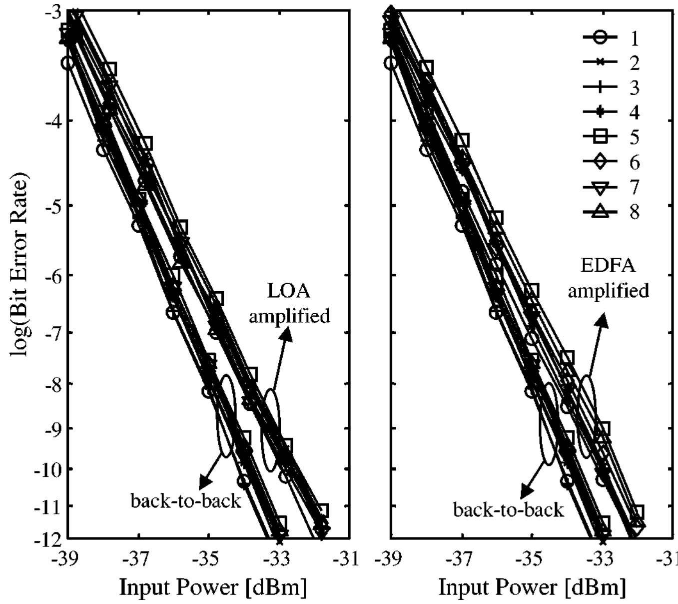

Fig. 3. BER performance of eight WDM channels using (a) LOAs and (b) EDFAs.

average power of $+3$ dBm. Next, the signals were sent into the second intermediate node (Node2) which is constructed with the second attenuator (Att2) and the second LOA (LOA2). The total power at the output of Node2 was adjusted to $+3$ dBm. The current injected into the LOAs was about 350 mA. After Node2 the signals were coupled to the receiver node.

In the receiver node, an optical demultiplexer was used to separate the WDM signals, followed by an optical attenuator (Att3) and an optically preamplified receiver. The optically preamp receiver consisted of an EDFA gain block, a 0.8-nm bandwidth optical bandpass filter, a 10-Gb/s receiver module, and a clock/data recovery module. The received signal was evaluated with a bit-error-rate (BER) analyzer to determine the performance of the LOA-based WDM system. For BER measurements we used a nonreturn-to-zero (NRZ) data pattern and the receiver sensitivity was measured at the input of the optically preamplified receiver. The LOAs in the experiment exhibit a gain of 13 dB, a noise figure of around 8 dB, and polarization dependent gain of 0.5 dB.

Fig. 2 shows spectra of the eight WDM channels as observed in the output of the transmitter node (a), and in the input of the receiver node (b). No visible gain tilt is present in the signal spectrum. This is due to the very flat gain spectrum of individual LOAs. The averaged optical signal-to-noise ratio (OSNR) after two LOAs is approximately 32 dB, enabling performance assessments of $\mathrm{BER} = 10^{-9}$ or better.

Fig. 3 shows measured BER curves of the eight channels in the WDM system in Fig. 1 with LOAs (a) as well as EDFAs (b). For each case, back-to-back (BB) measurements, i.e., without intermediate nodes, are shown. All eight channels have an identical BER performance. Fig. 3(a) shows the BER curves of the LOA-based eight-channel WDM system. The BER performance of each WDM channel is in general very close to the BER performance of the WDM system using EDFAs. This extremely identical performance is due to the fact that the LOAs have uniform gain characteristics over a large bandwidth. The gain per channel is large enough to suppress the destructive effects of optical noise on the demultiplexed WDM signals at the receiver. Compared to the BB receiver sensitivity, a power penalty of approximately 1 dB $(\mathrm{BER} = 10^{-9})$ was measured for the system using LOAs and EDFAs. This small penalty was caused by the beat product of the signal and spontaneous emission of the cascaded optical amplifiers. With a receiver sensitivity of $-$ 33 dBm and a laser power of $+$ 2 dBm per channel, the total loss budget was 46 dB of which 10 and 13 dB were caused by Node1 and Node2, respectively.

III. ADD-DROP EXPERIMENT

To assess the transient response behavior of the WDM system, the laser source 1, 3, 5, and 7 in Fig. 1 were switched on and off continuously at switching rates between 10 and 100 kHz. These rates of a few tenths of milliseconds anticipate the switching times of the next generation of the MEMS-based wavelength cross-connects or ADD–DROP multiplexers [4].

Fig. 4 shows eye patterns of inner channel 4 when the odd-numbered channels are switched on/off at 20 kHz. Other channels were observed to perform similarly. It can be seen in Fig. 4(a) that the eye patterns for the system trial using EDFAs show noise-like distortions due to gain transients, which are a result of poor dynamic behavior [5]. In contrast to the case of using EDFAs, the eye patterns observed in the LOA system trial, as depicted in Fig. 4(b), shows a clear open eye, which is identical to the nonswitched case, with no visible degradation at all. The absence of signal degradation in a switched environment is a result of the absence of gain transients in the LOA device [2].

Fig. 5 presents the measured BER performance of channel 4 for the dynamic wavelength ADD–DROP system. The curves show an extra power penalty of about 1 dB for the WDM system using EDFAs as a result of the EDFA gain transients. For the LOA-based WDM system no observable additional penalty due to the 20-kHz switching was found. It is important to note here that for the EDFA-based system the decision threshold of the BER analyzer had to be adjusted dynamically to achieve reasonable performance whereas the LOA-based system had a constant decision threshold, making a simpler and low-cost receiver design possible.

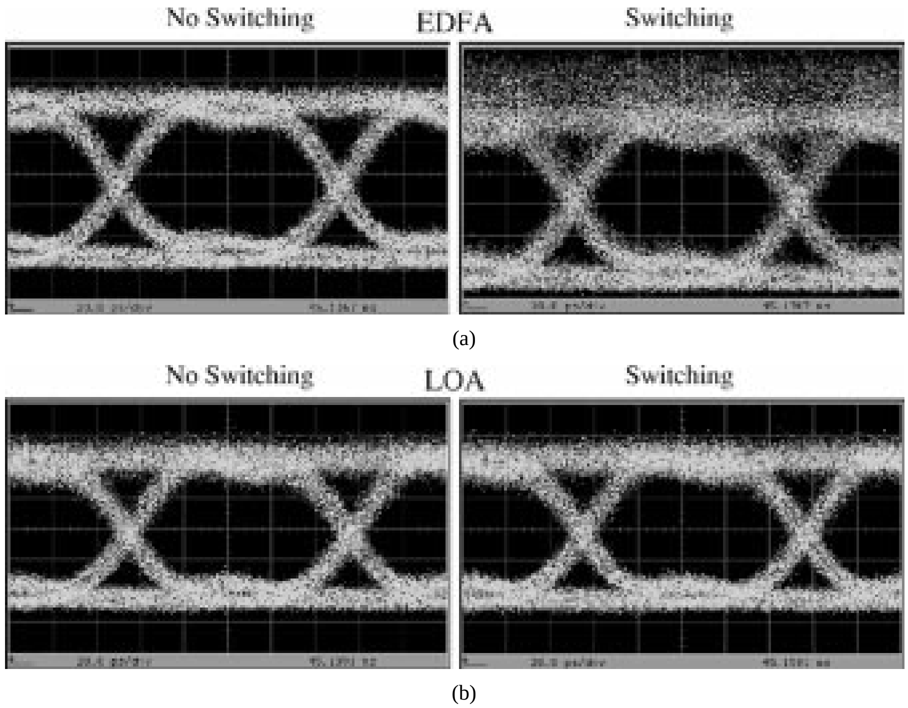

Fig. 4. Received eye patterns of 20 kHz switched and nonswitched WDM system using cascaded (a) EDFAs and (b) LOAs.

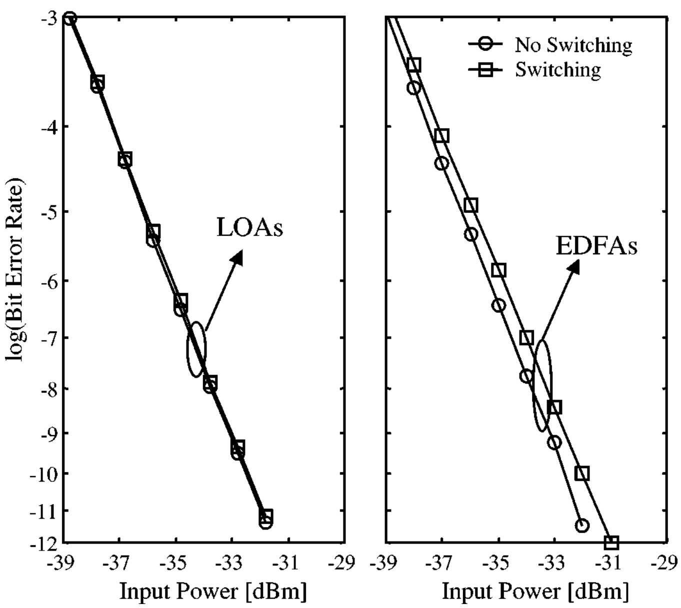

Fig. 5. BER performance of channel 4 with four channels switched on/off at a speed of 20 kHz in an optical system using (a) LOAs and (b) EDFAs.

IV. Conclusion

We have shown experimentally the performance comparison of using LOAs and EDFAs in an eight-channel 10-Gb/s WDM system. The experimental test-bed consisted of two intermediate nodes with a total node loss of 23 dB and two cascaded LOAs with a total gain of 26 dB to compensate for 46-dB aggregate loss between the transmitter and receiver.

The spectrum after amplification is shown to be flat, enabling a larger cascade of LOAs without the use of any form of gain-flattening mechanism. Bit-error-rate measurements showed similar system performance for a cascade of two LOAs and EDFAs, demonstrating WDM capability of LOA-amplified optical networks.

To simulate a dynamic and reconfigurable WDM environment, four of the eight wavelength channels were switched on and off at kilohertz speeds. The eye patterns and BER curves of the WDM system using EDFAs showed additional signal degradation due to amplifier gain transients. The LOA-based WDM system showed no observable signal degradation due to the switching. The absence of gain transients in LOAs enables the way to truly dynamic optical networks with fast protection switching, dynamic routing, and ADD–DROP capabilities.

Acknowledgment

The authors would like to acknowledge J.P. Turkiewicz for performing a part of the experiments and for the many valuable discussion on optical amplifiers.

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