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Investigating the Limits of Optical Packet Transmission Through Cascaded Transient-Suppressed EDFAs Without Regeneration or Active Gain Control

Benjamin J. Puttnam[†], Yoshinari Awaji and Naoya Wada
National Institute of Information and Communications Technology (NICT), 4-2-1, Nukui-kita, Koganei, Tokyo 184-8795, Japan.
E-mail: ben.puttnam@chalmers.se, {yossy, wada}@nict.go.jp.
[†] Currently with Photonics Lab, Dept. Microtechnology & Nanoscience, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Szilárd Zsigmond
Dept. of Telecoms. & Media Informatics, Budapest University of Tech. & Economics, Magyar tudósok körútja 2, Budapest 1117, Hungary

Abstract: Using a transmission loop, we show the maximum number of cascaded conventional-EDFAs is gain-transient limited for packet transmission and demonstrate error-free, noise limited packet transmission across 44 transient-suppressed EDFA's without active gain-transient control or regeneration.

OCIS codes: (060.2410) Erbium Fibers; (060.4259) Packet-Switched Networks

1. Introduction

The requirement for fine granularity, high capacity and scalable architectures in the next generation of optical networks has driven the development of a number of advanced network schemes where data is transmitted in sub-μs optical packets [1-4]. These optical packet switching (OPS) architectures maybe based on code, time or wavelength division multiplexing (WDM) but have a common requirement for optical amplification that is insensitive to input power fluctuations (IPFs) characteristic of packet transmission. The erbium-doped-fibre-amplifier (EDFA) has become the standard for point-to-point WDM systems but IPFs result in gain-transients and signal degradation, particularly when real-time packet receivers, with almost exclusively operate with fixed decision-threshold, are employed [5]. A common approach to minimise gain transients is optical gain clamping by a non-signal channel derived from either optical feedback [6,7] or electronic control [8]. However, as well as additional component costs, gain clamping reduces the available signal gain [7]. Electronic control of the pump drive current [9] has been proposed but has the additional disadvantage that gain adjustments to correct for IPFs on some channels affect all channels and, therefore, may induce amplitude variations on other throughput channels.

In addition to active compensation techniques, mitigation of gain transients has been achieved in OPS networks by utilizing fiber with a larger active area of erbium. This transient suppressed (TS)-EDFA has shown strong transient suppression over OPS timescales [10,11]. However, since EDFA's may be used in both transmission and optical processing within OPS nodes, it is important to consider how gain transients accumulate along large amplifer cascades. Here, we investigate the limits of the number of consecutive amplifiers that optical packets can traverse without regeneration and the impairments that limit it. We show that for a conventional (C)-EDFA, the number of cascaded amplifiers is limited by amplitude variations caused by dynamic gain effects where as the TS-EDFA is able to suppress transients beyond the point where accumulated optical noise prevents error free transmission.

2. Experimental set-up

A recirculating transmission loop was used to investigate and compare the performance of the TS-EDFA and C-EDFA in an OPS network link. The experimental set-up for the transmission experiments is shown in Fig. 1(a). Two signal channels were generated at the loop input. The first, λ_C, was operated continuously at a wavelength of 1543.3nm and modulated with a 10 GB/s non-return-to-zero (NRZ), pseudo-random-bit-sequence (PRBS) of length 2^{31}-1. The second, λ_B, transmitted 10 GB/s optical packets at a wavelength of 1548.8nm. The packet comprised a 32 bit 1010 header, required to identify packet arrival at the receiver, and a 4000 bit (400ns) NRZ 2^{11}-1 PRBS payload, selected to match the packet length, and a guard band of 400ns. Both packet and continuous channels were used to investigate impairments on transmitted packets, λ_B, and through cross gain saturation on λ_C. The loop contained two EDFA's, 2*40km spans of dispersion compensated single mode optical fiber, an isolator and polarisation controller. Variable optical attenuators (VOAs) were used to ensure the total input power at each fiber span was under 0dBm and the input power at each amplifier was approximately -16dBm on each recirculation. A packet receiver [5] was used to receive the optical packets and packet waveforms were also received using a digital sampling oscilloscope. The packet receiver was gated with an additional acousto-optic modulator (AOM), similar to those used to control the loop signals shown in Fig. 1(a), to isolate the output from a specific recirculation with a gating window of 350 μs. The loop round trip time was 393 μs and the full receiver set-up is shown in Fig. 1(b).

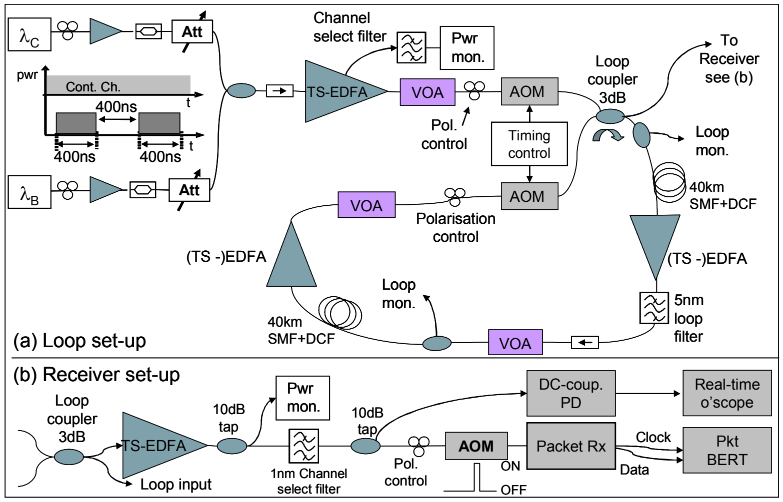

Fig. 1: (a) Experimental set-up for packet transmission over multiple EDFAs and (b) receiver set-up

Real-time bit-error-rate (BER) measurements of packets traversing the amplifier and fiber cascade were taken as a function of the number of recirculations and the receiver input power, with both TS-EDFA's and C-EDFA's used inside the loop. The maximum small signal gain and noise figure of the TS-EDFA was 25dB and 5dB respectively at -16dBm λ_B input power and the C-EDFA was selected to have similar characteristics. Additionally, the Opti-System simulation software was used to construct a theoretical model of the equivalent amplifier cascade. The simulation was intended to identify how many amplifiers could be cascaded before noise accumulation became critical and was based on the measured characteristics of the TS-EDFA and other loop components, but did not consider amplitude variation across packets due to transient gain dynamics. For comparison the theoretical model was used to make identical measurements to those obtained with the packet receiver.

3. Experimental results and discussion

Fig. 2 shows the minimum receiver input power required to achieve a $<1*10^{-9}$ BER as a function of the total number of cascaded C-EDFAs and TS-EDFAs together with the same measurement derived from the TS-EDFA simulation.

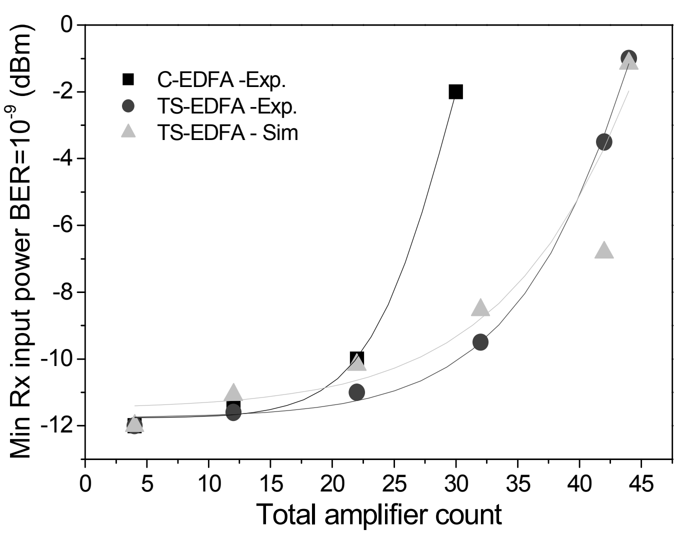

Fig. 2: Minimum receiver input power for a BER$<1*10^{-9}$ for C-EDFA, TS-EDFA and static gain TS-EDFA simulation

Fig. 2 shows that the optical packets maybe transmitted over a maximum of 44 amplifiers for the TS-EDFA, compared to 30 for the C-EDFA. Additionally, the measured BER values for the TS-EDFA show good agreement with the simulated results which assume only static EDFA gain. These results are significant since they show that the limit of the number of cascaded amplifiers for the specified BER ($<1*10^{-9}$) is limited by noise accumulation in the TS-EDFA and not by gain-transient induced amplitude variation in combination with the fixed threshold packet receiver as appears to be the case for the C-EDFA. Further evidence of this is shown in Fig. 3, which shows the probability density functions (PDFs) for 2 consecutively received packets. These were derived from the received digital waveforms and also used to estimate the Q-factor of received packets. After 44 TS-EDFA's, the PDF appears Gaussian with a Q-factor of approximately 6 (15.5dB), equivalent to the measured BER of $1*10^{-9}$, indicating noise accumulation as the primary source of degradation. After 30 C-EDFAs, where the same BER was measured, a 1dB lower Q-value was obtained and the PDF is non-Gaussian. This distortion arises from amplitude variations, not observed for the TS-EDFA, resulting from accumulated gain transients. These are also evident in the digital waveforms included as insets in Fig. 3 where it is evident that the amplitude variations occur primarily on the '1' signal level but also transferred to the '0' level in the PDF plot by the normalization process. Hence, for the C-EDFA the maximum number of cascaded amplifiers is limited by accumulated EDFA gain-transients before noise accumulation degrades the BER above $1*10^{-9}$. It is worth noting that the noise performance of both amplifiers, and therefore, the TS-EDFA cascade limitation, may be improved by reducing the 1nm bandwidth of the receiver filter used or by increasing the loop amplifier input power above -16dBm.

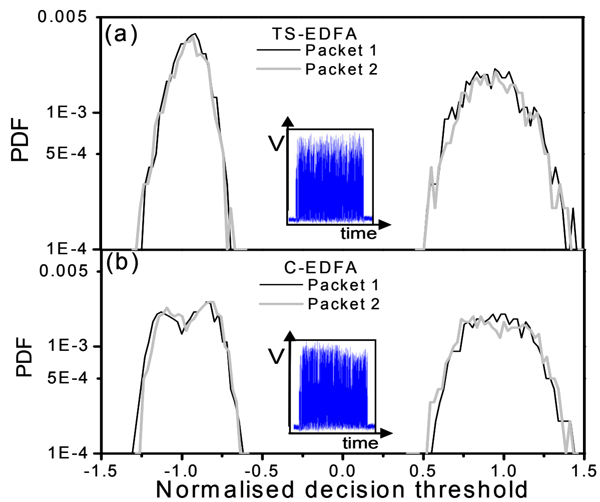

Fig. 3: PDF as a function of the normalized decision threshold after (a) 44 TS-EDFAs and (b) after 30 C-EDFAs

4. Summary and conclusion

We use a recirculating transmission loop to model a multi-hop OPS link. We find that, for optical packet transmission, the maximum number of cascaded conventional EDFA's is limited by gain-transient accumulation. We then demonstrate error-free transmission across 44 transient-suppressed EDFA's without active gain-transient control or optical regeneration, limited by accumulated optical noise. These results show that adopting a TS-EDFA is essential for OPS networks where many cascaded EDFA's are used for overcoming losses in transmission and optical processing.

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