Experimental investigation of transients in six cascaded AGC EDFAs and their suppression using a high-speed VOA

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Abstract: We investigate gain transient responses of an automatic gain control (AGC) EDFA with fast electrical feed-forward pump control. Even if each of the AGC EDFAs can well suppress the gain transients for add/drop operations with various switch speeds, the cumulative transients in cascaded AGC EDFAs give rise to a non-negligible impact. We demonstrate that a high-speed variable optical attenuator (VOA) can suppress such cumulative transients. Error-free operation of a surviving channel under the instantaneous load and unload condition with six cascaded AGC EDFAs is confirmed. The burst mode signal is 7-ms duration with 16-dB range.

Keywords: EDFA transient suppression, optical fast circuit switching network

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

Dynamical switching of optical signals in the optical domain receives increasing importance as a cut-through operation or protection/restoration in optical domain is highly demanded due to cost and energy pressure. Because fast and large changes of the input power levels to erbium-doped optical amplifiers (EDFAs) cause dynamic gain transients and hence deteriorate transmission quality, the conventional reconfigurable optical add/drop multiplexer (ROADM) systems have been significantly limited in its flexibility and scale as well as reconfiguration speed. In fact, even though several techniques have been proposed to suppress the transients of one-stage EDFAs [1, 2, 3, 4, 5], the cascaded operations of the EDFAs with such techniques would still suffer from severe cumulative transients in particular for high-speed switching operation [6, 7], which remains substantially unsolved to date to our knowledge. Fundamentally, no matter how fast and properly the pump power is controlled, the intrinsic dynamics of the erbium ions cannot be completely controlled externally.

On the other hand, a high-speed variable optical attenuator (VOA) with a response time of less than 1 μ s has been adopted to suppress such remnant transients in conjunction with a fast electrical feed-forward pump control to achieve better suppression of gain excursions within much faster settling time [8]. A gain excursion of less than 0.19 dB per unit was realized by the AGC EDFA with a VOA for a 20-channel add/drop equivalent operation.

This study is an extension of [8] in particular to a cascaded operation. Firstly, we investigate the transients of the AGC EDFA for various optical switches. Secondly we prepare six AGC EDFAs with feed-forward pump control and one high-speed VOA for investigating their cascaded transient performance. We suppose to change the input power of the AGC EDFAs

by 16 dB using an optical switch with nano-second order switch speed. We demonstrate that the high-speed VOA can suppress the accumulated transients to 0.8–2 dB and the bit error rate (BER) of a surviving channel stays error free. To the best of our knowledge, this is the best result of ever reported transient performances while the cascaded operation emulates one of the severest case in terms of the input power dynamic range and the add/drop switch speed.

2 Transient response check for optical switches

We prepared three kinds of optical switches that offer different switching speed each other in order to investigate the transient overshoot and undershoot of the single stage operation of the AGC EDFA without a high-speed VOA [8]. The experimental setup is shown in Fig. 1 (a). We input two wavelengths to the AGC EDFA, 1550.116 nm and 1550.918 nm. The wavelength channel of 1550.116 nm is continuously input and we call this surviving channel, while the wavelength channel of 1550.918 nm is added or dropped using optical switches and we call this aggressive channel. The AGC EDFA input power dynamic range was set to 16 dB that corresponds to sudden add/drop of 39 channels in a 40-channel system. In other words, we emulated the largest input power change on a 40-channel WDM transmission in 100 GHz ITU-T grid in C-band. Here we used the 2-channel scheme because our focus here is to investigate the EDFA transients due to input power changes. However, we note that evaluations in a full WDM scheme should be conducted to apply an EDFA to a WDM transmission system. This is our next target.

Fig. 1 (b) shows the measured waveform of fast optical switch whose 10%–90% switching time is less than 70 ns, Fig. 1 (c) that of MEMS switch whose switching time is less than 500 μ s, and Fig. 1 (d) that of LCOS based WSS whose switching time is less than 40 ms. All the measured transient over-

Fig. 1. Experimental setup and measured waveforms for three kinds of optical switches

shoots and undershoots are less than 0.5 dB. They are well suppressed for single EDFA operation while the faster optical switch provides the larger transients.

3 Cascaded operations with high-speed optical switch

Fig. 2(a) shows the experimental setup for a cascaded operation. We cascaded six feed-forward pump controlled AGC EDFAs. We used the fast optical switch for adding/dropping the aggressive channel in order to examine the severest case according to the experimental results shown in Sec. 2. The optical switch was driven by a function generator and generated an optical burst pulse with duration of 7 ms and a duty cycle of 7%. We note that this condition is after [6] for reference. The input levels of the surviving and aggressive channels to each AGC EDFA were -20 dBm and -4 dBm, respectively. However, we have slightly adjusted and optimized input power levels such that the transients were suppressed as much as possible. We load 10-Gbps NRZ $2^{31} - 1$ pseudo-random bit sequence (PRBS) on the surviving channel in order to monitor its BER performance since the impact of add/drop of the aggressive channels is larger for the surviving channel than the aggressive channels themselves. The optical attenuators (ATTs) emulate either the span or node losses. The optical band-pass filters (BPFs) after EDFAs eliminate the ASE noise of EDFAs and the bandwidth is set to 2 nm.

Fig. 2(b) shows the cumulative transient overshoots and undershoots at each stage. The figure indicates that the transients tend to linearly accumulate in dB, and that even small transients per stage will cumulatively give rise to a non-negligible impact at the receiver end. Fig. 2(c) shows the measured waveform after the 6th EDFA. Due to the feed-forward control rather than feed-back control of pump lasers, we did not observe any oscillatory behavior

Fig. 2. Experimental setup and measurements of cumulative transient effects

as reported in [6].

4 Suppression of cumulative transients using a high-speed VOA

In order to suppress the cumulative transients, we inserted one high-speed VOA after the 6th EDFA of the experimental setup shown in Fig. 2 (a). The high-speed VOA can reduce both overshoot and undershoot. The detailed high-speed VOA operation is described in [8]. In the simple terms, the high-speed VOA loss is reduced in order to offset the undershoot when the burst signal is added and the high-speed VOA loss is increased in order to eliminate the overshoot when the burst signal is dropped. The measured waveforms show that the high-speed VOA can effectively suppress the overshoot of the surviving channel to less than 1 dB as shown in Fig. 3 (a). The undershoot of the surviving channel was still 1.9 dB however the suppression of the undershoot will be more improved by optimizing the high-speed VOA control parameters. The effects of transient suppression by high-speed VOA were also observed in eye diagrams shown in Fig. 3 (b). Many spots are observed outside of the eye in Fig. 3 (b) without VOA case (left). The

Fig. 3. Transient suppression by high-speed VOA after 6 EDFAs

Fig. 3 (c) shows the measured BER characteristics. The power penalty at the BER of 10^{-9} without aggressive channel was 0.9 dB, that with aggressive channel and without high-speed VOA was 2.3 dB, and that with aggressive channel and high-speed VOA was 1.3 dB. Consequently, the BER degradation due to the accumulation of the EDFA transients was 1.4 dB and inserting a high-speed VOA after 6 EDFAs can improve the power penalty by 1 dB in this experiment.

Even in the presence of the largest input power change in a 40-channel ROADM network, the six cascaded AGC EDFAs with electrical feed-forward pump control can provide a stable operation of the surviving channel with the aid of the high-speed VOA. We have confirmed that better algorithm to control the VOA would better suppress the overshoot and undershoot. The other alternative would be to deploy high-speed VOAs at each of the EDFAs that would suppress the accumulation of the transients.

5 Conclusion

In the paper, we have investigated transient responses of an AGC EDFA with electrical feed-forward pump control. Firstly we confirmed the AGC EDFA could well suppress the transients for a sudden input power change using optical switches with various switch speeds nevertheless we also confirmed faster switch speed imposed larger transients. Secondly, we experimentally demonstrated that even small transients per AGC EDFA cumulatively produced a non-negligible impact at the receiver end in cascaded operations. Finally, we demonstrated a high-speed VOA following the six cascaded AGC EDFAs could suppress the accumulated transients and improve the power penalty. Error-free operation of the surviving channel during instantaneous load and unload of a 7-ms burst signal with 16-dB dynamic range in the six cascaded AGC EDFAs was confirmed. To the best of our knowledge, this is the best result ever reported while we here emulated one of the severest case for EDFA transients in terms of the input power dynamic range and the switch speed of add/drop operations.

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