Transient effect to small duty-cycle pulse in cascaded erbium-doped fiber amplifier system

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Abstract. Factors that affect the transient effect on small duty-cycle pulse in a cascaded erbium-doped fiber amplifier (EDFA) system are studied in simulation and experiment. The considered factors consist of the numbers of cascaded EDFAs, the peak power and the extinction ratio of optical pulse, with results showing that the optical pulse will be severely distorted by the transient effect of EDFA. The distortion becomes more serious with the increase of the three parameters. To avoid or mitigate the transient effect, a method of adding another optical signal with a different wavelength to the objective pulse is employed in the experiment. The experimental results show that this method could effectively restrain the transient effect in a cascaded EDFA system. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.52.2.025006]

1 Introduction

In the past few decades, erbium-doped fiber amplifiers (EDFA) have been widely used due to their high gain, low noise figure and broad gain spectrum. Generally speaking, there are many EDFAs cascaded in a long-distance optical fiber communication system. Due to the slow gain dynamics of EDFA, the transient effect[1–7] that can significantly affect the amplifying performance of amplifiers, especially in a cascaded EDFA system, is inevitable in EDFA. Presently, on the one hand most research on transient effect has been done in the wavelength division multiplexing (WDM) system where the duty cycle of the signals is usually 50%.[8–12] In this research, the number of cascaded EDFAs, switching time, and signal powers were found to influence the transient effect in WDM system.[9–12] However, if a small duty-cycle pulse with a long period and narrow pulse width is used, the aforementioned research might be insufficient to describe the amplify procedure in this situation. On the other hand, a small duty-cycle pulse is usually used in fiber-sensing technology, such as coherent optical time-domain reflectometry (COTDR) that is used to monitor the faults in the long-distance cascaded EDFA system.[1] When a small duty-cycle pulse transmits in the cascaded EDFA system, the EDFA transient effect will bring about an optical surge, pulse distortion, and will be accompanied by nonlinear effects. This will severely affect the quality of the sensing and limit the monitor distance. Therefore, the transient effect is an obstacle that must be overcome when a small duty-cycle pulse is used in cascaded EDFA system.

In this paper, the transient effect on the small duty-cycle pulse when the pulse is employed in cascaded EDFA system is studied in both experiment and simulation. The research shows that the probe pulses are distorted due to the transient effect, and the number of cascaded EDFAs, peak power, and the extinction ratio of a small duty-cycle pulse are the main

influencing factors on the transient effect. Thus, the distortion becomes more serious when the values of the three factors increase. And a method is proposed and successfully used to suppress the transient effect in a cascaded EDFA system.

2 Design of Experiment and Simulation

The experiment setup is shown in Fig. 1, an ECL (external cavity laser) with a wavelength of 1561.42 nm used as a source, and an optical pulse is generated by an acousto-optic modulator (AOM) with the extinction ratio (ER) of 50 dB. Here ER is defined as the ratio of the peak power to the base power of an optical pulse. The modulated optical pulse is launched into the cascaded EDFA system. In the cascaded system, the length of each fiber section is 85 km. The gain of each EDFA is 17 dB and the noise figure. of EDFA is 4.5 dB. To observe the distortion of a small duty-cycle optical pulse, a 5/95 optical coupler is placed after each EDFA,
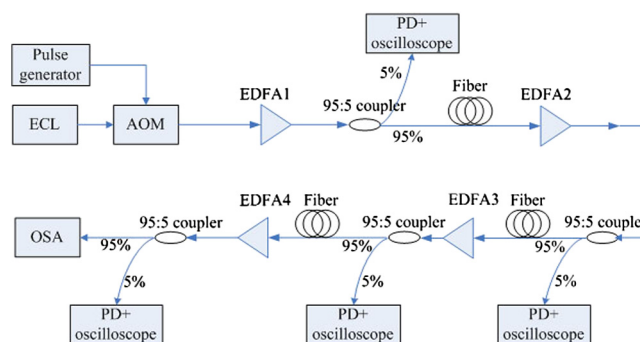
Fig. 1 Experimental Setup for measurement of transient effect in cascaded system with four EDFAs, ECL: external cavity laser; AOM: acousto-optic modulator; OSA: optical spectrum analyzer; PD: photodetector.

Table 1 Parameters of EDFA in simulation.

Parameter	Value	Parameter	Value
Core raidus	2.32 μm	Er ion density	1e + 25 m^{-3}
Er doping raidus	2.32 μm	Pump power	(pre)12 dBm/ (Post)11 dBm
Numerical aperture	0.23	Loss at 980 nm	3 dB/m
Er metastable lifetime	10 ms	Length of EDF	5 m

and the output of 5% port is put into photodetector (PD), then the output of PD is directed to an oscilloscope (Agilent MSO6104A) to monitor the pulse shape. The PD's conversion gain of RF-output is 10^3 V/M.

To compare with the experimental results, an EDFA is specially designed for simulation using the "Er doped fiber dynamic" module, which is specially designed for the time scales on the order of microseconds or longer in the OptiSystem software, and the details of the algorithm for this module is based on the solution of the propagation and rate equations for transitions between the upper and lower levels of a two-level system approximation.[13] The parameters of the devised EDFA in simulation are shown in Table 1, the emission and absorption cross-sections are set to default by the software. In the simulations, the parameters of EDFA are fixed, and the optical configuration used is the same as that in the experiment shows in Fig. 1. The evolutions of pulse shape in a cascaded EDFA system are monitored through the 5% port of the coupler after each EDFA. The influences of the numbers of cascaded EDFAs, the ER and peak power of the input pulse on the transient effect are studied separately, both in the experiments and the simulations, for comparisons in the next section.

3 Results and Discussions

3.1 Transient Effect with the Increasing Numbers of Cascaded EDFAs

In this part we focus on the influence of the number of cascaded EDFAs on the transient effect. In the experiment and the simulation, the width of optical pulse is 5 μs with the period of 50 ms, and the peak power and the ER of the pulse are 0 dBm and 50 dB, respectively. The output pulse shapes from experiment and simulation are shown in Figs. 2 and 3, respectively. The values of peak pulse power and the power of accumulated amplified spontaneous emission (ASE) are compared in Table 2.

The tendency for pulse distortion due to the transient effect in EDFA is nearly the same in both the experimental and simulated results. Pulse distortion and power accumulation of ASE can be seen in both results. According to Table 2, the power of ASE becomes higher and higher with the increasing number of cascaded EDFAs because the power of ASE is accumulated in the cascaded EDFA system. On the contrary, the pulse peak power decreases with the increasing number of cascaded EDFAs. Therefore, the pulse distortion becomes more and more serious with the increased number of cascaded EDFAs, which are shown
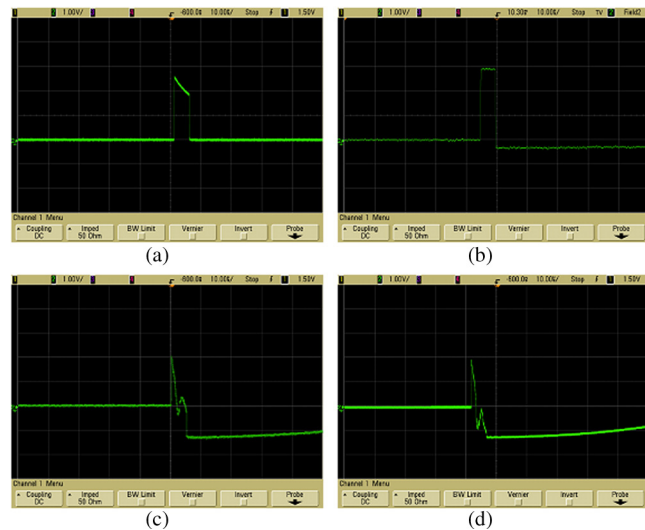

Fig. 2 Experimental results after four different EDFAs in system, (a) after EDFA1; (b) after EDFA2; (c) after EDFA3; and (d) after 4 EDFA, reading values of the four pictures are 10 μs per division horizontal and 1V per division vertical.

in Figs. 2 and 3. The pulse distortion is very serious in (c) and (d) of Figs. 2 and 3, the 5 μs pulse is nearly split into two pulses. The reason for this is that the power of ASE is too high while the pump power of EDFA is finite. When many erbium (Er) ions are consumed by ASE, the remaining ions cannot adequately amplify a pulse with a width of 5 μs, a pulse with a width of 1 or 2 μs may exhaust the remaining Er ions. As Er ions resume over time, another part of the pulse can thenbe re-amplified, so the split output pulse can be seen both in the experiment and the simulation. In brief, the transient effect is enhanced with the increasing number of cascaded EDFAs and therefore pulse distortion is more serious.

3.2 Transient Effect with Different ER

The condition of the experiment and the simulation in this section is the same as Sec. 3.1, except that the peak power of the pulse is 10 dBm and another continuous wavelength (CW) laser is added to the system to change the ER of the optical pulse. The peak power of the optical pulse is unchanged, and the ER of the optical pulse is changed by changing the power of the CW laser. The output pulse shapes of the second EDFA is distorted, and the power difference of a single pulse is changing with the ER of the optical pulse, with the results of both experiment and simulation are given in Fig. 4, the ERs of the pulses in Fig. 4 are 5, 12, 15, and 21 dB, respectively. From Fig. 4, we find that the ER of signal can affect the pulse distortion. Distortion of the output pulse becomes more serious with the increase of ER, the reason being that when the ER is lower, the noise level is higher. The noise of low ER pulse can consume more Er ions on the metastable level when it is amplified. So when EDFA is amplifying a pulse with a low ER, it cannot accumulate too many Er ions on the metastable level. As a result, the pulse distortion can be slighter. However, if you reduce ER, for example, the sensing distance of fiber sensor becomes shorter when the ER is low. As a result, a method is needed to restrain the transient effect without reducing the ER.
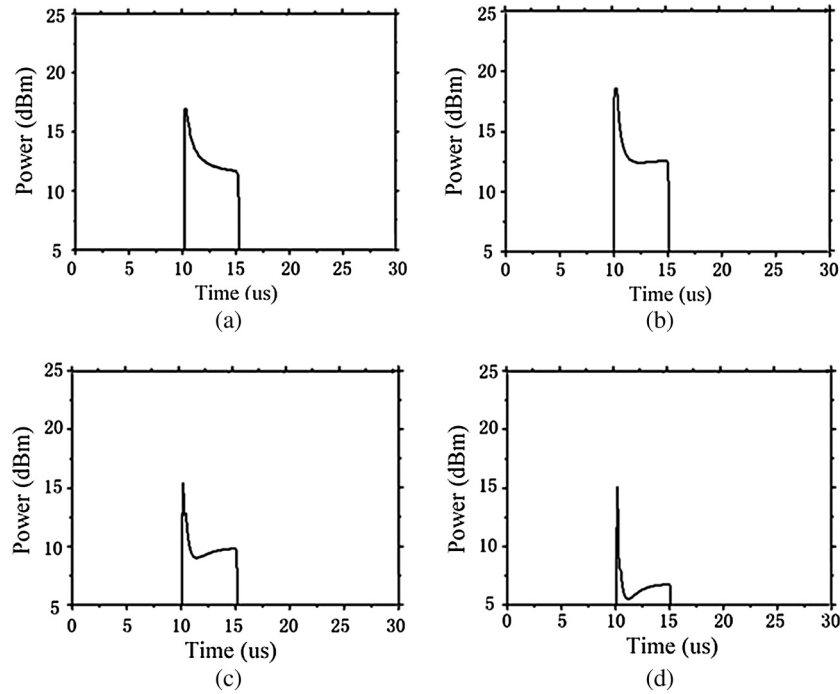
Fig. 3 Simulation results for the four EDFAs, (a) is the result of EDFA1, (b) is the result of EDFA2, (c) is the result of EDFA3, and (d) is the result of EDFA4.
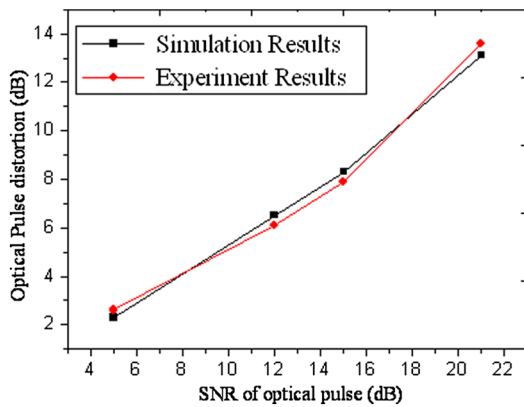
Fig. 4 Pulse distortion with different ER.

3.3 Transient Effect with Different Peak Power of Input Pulse

To study the influence of peak power of input pulse on the transient effect, the pulse with fixed ER of 50, period of 50 ms, pulse-width of 5 μs and the peak powers of the pulses are −5, 0, 5, and 10 dBm are employed in the experiment and simulation. The output pulse shapes from the second EDFA of both the experiment and simulation are given in Fig. 5

In Fig. 5, we see that the higher the peak power, the more serious the pulse distortion. This is because when period and pulse-width of a small duty-cycle pulse is the same, the Er ions accumulated on metastable level is equal, and the transient gain of EDFA is the same for pulses with different peak powers. As a result, if the input power is higher, the output from EDFA will be higher, and the pulse distortion will be more serious.

Table 2 Output signal power (unit: dBm).

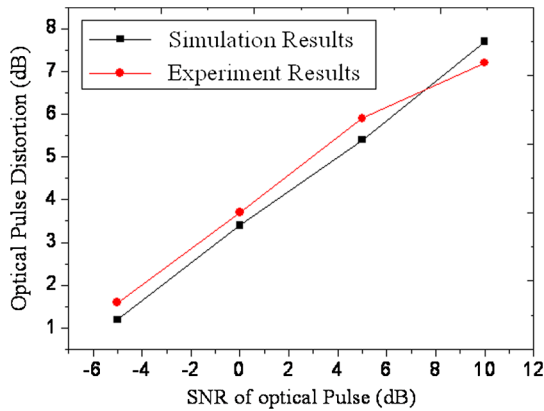| EDFA	Experimental results		Simulation results	
	Pulse peak power	Accumulated ASE	Pulse peak power	Accumulated ASE
EDFA1	17.16	−5.2	17.2	−5.15
EDFA2	17.78	0	17	−0.2
EDFA3	15.3	1.8	15.4	2.3
EDFA4	15.05	2.3	12.8	3.36

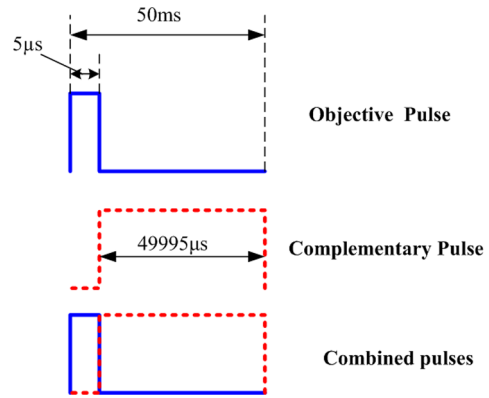**Fig. 5** Pulse distortion with different peak power of input pulse.

Fig. 7 The diagram of the combined pulses.

4 Method to Restrain the Transient Effect

Small duty-cycle pulse is commonly used in the long-distance distributed fiber-sensing system. In this situation, the performance of a sensor would be limited due to the distorted pulse induced by the transient effect of EDFA. The transient effect is more notable in a cascaded EDFA system, such as transatlantic optical fiber communication, where the COTDR is usually used for nondestructively measuring the attenuation of a fiber link and locating the discrete defects. Therefore, it is significant to mitigate the transient effect in the long-distance sensing. To restrain the transient effect to a small duty-cycle pulse in cascaded EDFA system, the method adopted in the experiment is to add another signal with a different wavelength. The experimental setup is shown in Fig. 6. Compared to Fig. 1, we add an additional pulse (marked as complementary pulse) with a wavelength of 1562.23 nm whose duty cycle is complementary with the small duty-cycle pulse (called objective pulse) being amplified. The arrangement of the combined pulses is sketched in Fig. 7, and two pulses are combined and put into the cascaded EDFA system at the same time. By using this method, the amplified optical pulses in the experiment are shown in Fig. 8. It can be found that slight pulse distortion occurs after it transmitting through four EDFAs, which might be because of the small gaps between the two pulses induced by the not quite ideal electric pulse signal from our generator and the two incompletely complementary pulses. However, the distortion would not seriously affect the detection results in the sensing system. Therefore, there are two points that should be noted in practical application. One is that the peak power
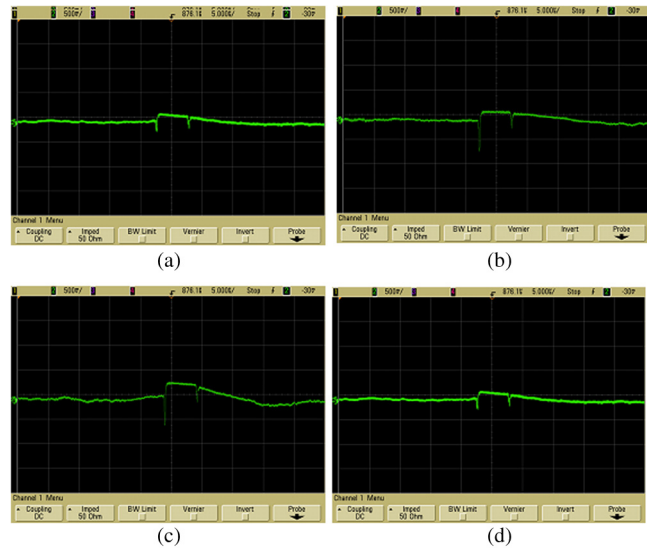

Fig. 8 Experimental results after four different EDFAs in system, (a) after EDFA1; (b) after EDFA2; (c) after EDFA3; (d) after EDFA4, reading values of the four pictures are 5 μs per division horizontal and 500 mV per division vertical.

of the two pulses should be equal; if not, there will still be pulse distortion and accumulated ASE caused by the transient effect. Another is that the two pulses should be completely complementary, otherwise, there will still be pulse distortion caused by the transient effect. When the pulse period is larger than 2 μs, the transient effect will begin to affect the objective pulse found in the experiment and simulation.
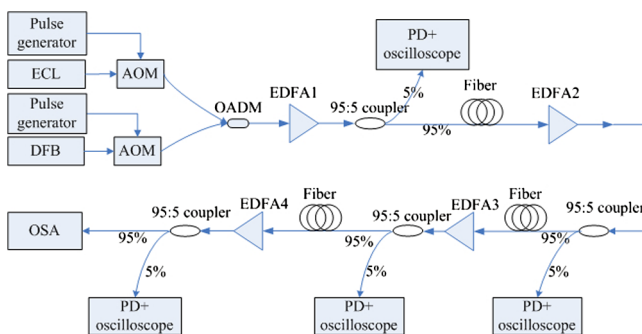
5 Conclusion

In this paper, the pulse distortion caused by the transient effect in cascaded EDFA system is successfully observed, and the factors that affect this effect are studied in the experiment and simulation. The factors include the number of cascaded EDFAs, ER, and peak power of the input pulse. Results show that the pulse distortion caused by the transient effect of EDFA is more serious with the increase of the three different factors. Moreover, to reduce the harm caused by the transient effect, a complementary pulse is added to the objective pulse being amplified, and the experimental results show that this method can effectively suppress the transient effect.

Fig. 6 Experimental setup to restrain the transient effect DFB: distributed-feedback lasers; OADM: optical add-drop multiplexer.

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