The Effect of Transient Gain Compression in a Saturated EDFA on Optical Time Domain Reflectometry Testing

W. I. Way, Y. W. Lai, and Y. K. Chen

***Abstract*— This paper examines optical-time-domain-reflectometry (OTDR) pulse distortion due to transient gain compression in a saturated erbium-doped fiber amplifier (EDFA) and the resultant effect on testing long-haul optical fiber systems.**

OPTICAL time domain reflectometry (OTDR) has recently become a popular technique for locating breaks and measuring return/transmission losses along optical fiber links. However, as the length of the link becomes longer owing to the installation of erbium-doped fiber amplifiers (EDFAs), the dynamic range of a conventional OTDR must be increased correspondingly. The dynamic range of a conventional single-pulse OTDR can be maximized by increasing the peak power or the duration of the probe pulse, by reducing the receiver noise, or by using digital signal processing techniques. In order to increase the peak power of a probe pulse and the sensitivity of a receiver, an EDFA can possibly be used simultaneously as a power amplifier and a preamplifier for the OTDR [1]. This appears to be an attractive approach because the OTDR and the EDFA can be integrated into a single measurement unit. EDFAs can also be used as in-line amplifiers to enhance the dynamic range of an OTDR [2], [3]. In this letter, however, we point out a fundamental problem with using a conventional OTDR together with a saturated power or in-line EDFA [4].

The 100–300 ms gain recovery time constant [5] in a saturated EDFA makes the amplifier exhibit a high-pass filter characteristics in response to a large input optical pulse, with a roll-off corner frequency around a few hundred Hz [5], [6]. Although this phenomenon does not affect high-bit-rate signals, it causes the important low frequency components (<a few hundred Hz) of the OTDR pulse to be gain compressed. The fact that the low frequency components are indispensable to a healthy OTDR trace is because the detected backscattered signal has a long time constant of 109 ms when the backscatter attenuation is 0.2 dB/km. This long time constant implies that all low frequencies below 1/(2.p.(109 ms)) ≈ 1.5 KHz are necessary frequency components. Furthermore, for future ultralong-distance systems that require repetitive OTDR pulses with a period of as long as a few hundred milliseconds, there will be a corresponding spectral line at a few hertz. For example, a 1000 km link will require an OTDR with a pulse repetition period of 10 ms, which gives a spectral line at 16 Hz. Therefore, an EDFA which is saturated (and with low frequency components suppressed) due to an OTDR pulse with a high peak power or a large pulse duration will result in a distorted backscattered signal and a correspondingly distorted OTDR trace.

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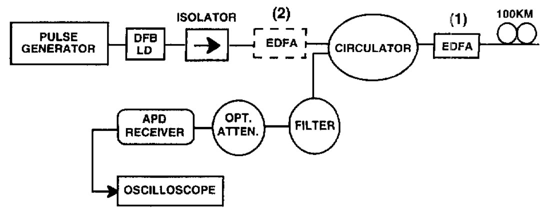

Fig. 1. Experimental setup I with bi-directional EDFA (location (1)), and experimental setup II with unidirectional EDFA (location (2)).

We carried out an experiment and a computer simulation to examine the phenomenon described above. The first experimental setup is shown in Fig. 1 in which the EDFA was placed after the optical circulator (location (1)). An HP 8146A OTDR was modified by replacing its Fabry-Perot laser with a DFB laser and an optical isolator, and by inserting an optical filter and an attenuator between the 3-dB coupler and the APD receiver. The pulsed DFB laser had a wavelength of 1.549 mm and a peak power of −10 dBm. An EDFA working as a power amplifier (and as a preamplifier for the reflected signal) was connected immediately after the 3 dB coupler. The maximum output saturation power and the small signal gain of the EDFA were 8 dBm and 19 dB, respectively. Four spools of single-mode optical fibers with a total length of 100 km were connected after the EDFA. The optical filter had a 3 dB bandwidth of 2 nm to eliminate most of the amplified spontaneous emission noise. An optical attenuator with up to 24 dB attenuation was used to prevent the highly sensitive APD receiver from being saturated. The InGaAs APD receiver has a bandwidth of 400 KHz, and an avalanche gain of 15. When the EDFA was not used, we obtained a regular OTDR trace, as shown in Fig. 2(a), when the pulse width was set at 15 ms. The detected pulse and the

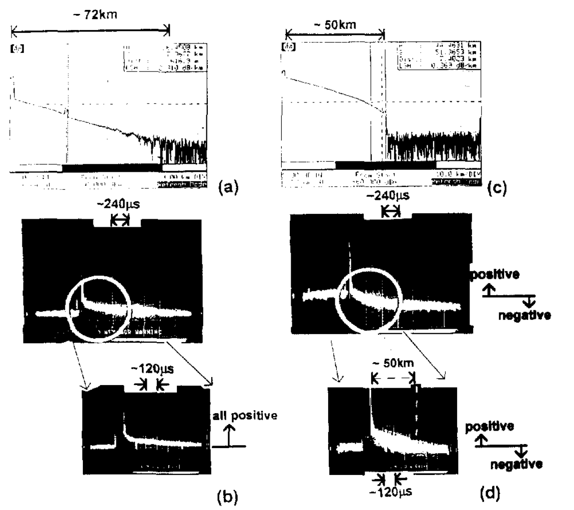

Fig. 2. OTDR traces without (a) and with (c) a saturated EDFA, and the detected backscattered signal without (b) and with (d) a saturated EDFA.

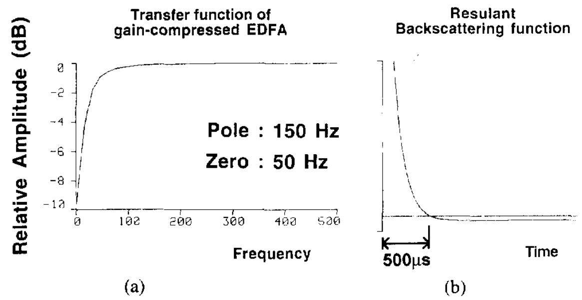

Fig. 3. Simulation results: (a) the transfer function of a gain-compressed EDFA, and (b) the resultant OTDR backscattering function.

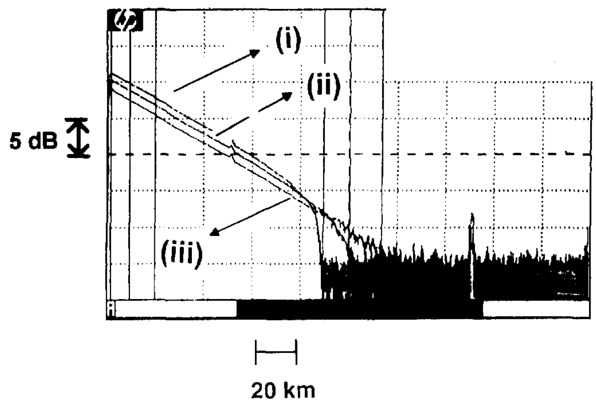

Fig. 4. Three OTDR traces showing the effect of increasing EDFA pump power. The pump laser was biased at (i) 195 mA, (ii) 162 mA, and (iii) 129 mA. The OTDR trace bending became less severe as the pump bias decreased.

associated backscattered signal are shown in Fig. 2(b). A part of the backscattered signal is enlarged to show that the entire backscattered trace has a positive value (with respect to a reference line). After we added the EDFA before the OTDR, the OTDR trace was disappointingly bent at a very short distance (~50 km in this case), as shown in Fig. 2(c), and the dynamic range was degraded instead of enhanced. This result is caused by the saturated-EDFA induced pulse distortion, as explained earlier. Fig. 2(d) shows that as the low frequency components of the pulse experienced gain compression, the detected backscattered signal, which is obtained from the convolutions of the distorted pulse, the backscattering impulse response of the fiber, and the impulse response of the receiver, became negative (with respect to a reference line) after a certain amount of propagation time. From the enlarged part of the backscattered signal, we can see that after about 500 ms (corresponding to the 50 km in Fig. 2(c)), the amplitude became negative. Since the OTDR displays logarithmic values of the backscattered signal, a normal trace can no longer be obtained with the resulting negative values (with respect to a reference line). This is why the OTDR trace in Fig. 2(c) bends short at about 50 km.

In Fig. 2(d), the dc level before the pulse due to the filtered ASE is negligible ($<10^{-4}$ mV). This was confirmed both by careful measurement and by calculations.

To confirm the measured results, we modeled the transient gain-saturated EDFA as a lead compensator [6] with a zero and a pole at 50 and 150 Hz, respectively, and its frequency response is given in Fig. 3(a). Assuming the DC-coupled APD receiver has a flat frequency response, we obtain the backscattered signal shown in Fig. 3(b). This simulated result matches well with the experimental result and exhibits negative values for the trace after $t \approx 500$ ms.

In the original experimental setup where the EDFA was placed after the optical circulator (location (1)), the EDFA experienced gain saturation not only from the forward-propagating pulse launched from the laser, but also from the backscattered pulse from the long optical fiber link. To avoid this additional gain saturation, we tried a second experiment by placing the EDFA before the optical circulator (as shown by the dashed box or location (2) in Fig. 1). In this case, the EDFA functioned as a power amplifier only. The OTDR trace was then observed to have improved significantly—the curve bent at a distance of close to 90 km instead of 50 km (as was the case in Fig. 2(c)). Similar arrangement was also demonstrated in ref. [7].

We also noticed that when the OTDR pulse was reduced from 15 ms to 500 ns or 125 ns, as was done in [1], the distorted OTDR trace was significantly improved, owing to the far lower degree of gain saturation in the EDFA. Incidentally, it is worth noting that the combination of short OTDR pulses with power EDFAs can be used in local loop applications to achieve both a high resolution and a high dynamic range [7], [8]. Another observation was that, when the EDFA pump power level was increased, the OTDR trace bent at a even shorter distance, as shown in Fig. 4. This is because the time constant decreased as the pump power increased [5]. In addition, the phenomenon in Fig. 2(c) was observed not only for a saturated power EDFA, but also for saturated in-line EDFAs. This is illustrated in Fig. 5 for a case of three

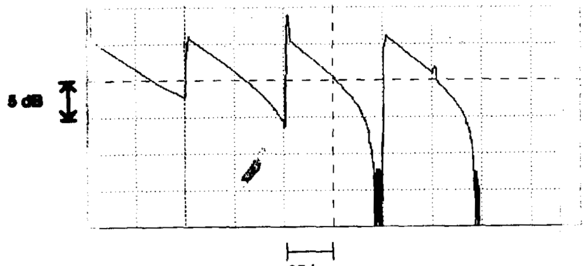

Fig. 5. OTDR trace with three cascaded in-line EDFAs (with no optical filter between EDFAs). The OTDR trace bending can be clearly observed after the second EDFA.

cascaded EDFAs (without optical filters in between stages). The bending of the OTDR traces after the second EDFA was quite obvious.

A software signal processing technique can possibly be used to resolve the fundamental problem that we presented (when the EDFA is placed at location (1) in Fig. 1). This technique is feasible because we can calculate the saturated EDFA impulse response as shown in Fig. 3, and accordingly correct it by software processing. In other words, by storing all different pole and zero parameters that correspond to different OTDR pulse widths (for different EDFA saturation conditions). We can obtain healthy OTDR traces by applying the software correction processing. However, due to the uncertainties in the pulse height—the pump power levels, etc., during actual system operations—software corrections may not be as accurate as one wishes.

In conclusion, we found that OTDR pulse distortion can occur (and thus a distorted OTDR trace) in a saturated EDFA. This is mainly due to (1), the combination of the large input optical pulse and the correspondingly shortened transient gain recovery time constant, and (2), low frequency components are important to OTDR backscattered signals. We also found that unidirectional EDFA amplification of OTDR signal is a better arrangement than bi-directional EDFA amplification because the additional gain saturation due to backscattered pulse peak can be avoided.

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REFERENCES

[1] L. C. Blank and D. M. Spirit, "OTDR enhancement through erbium fiber amplification," *Electron. Lett.*, vol. 25, pp. 1693–1694, Dec. 1989.
[2] Y. Sato and K. Aoyama, "Optical time domain reflectometry in optical transmission lines containing in-line Er-doped fiber amplifiers," *J. Lightwave Technol.*, vol. 10, pp. 78–83, Jan. 1992.
[3] Y. Horiuchi, S. Yamamoto, S. Akiba, and H. Wakabayashi, "Highly accurate fault localization over 4580 km optical amplifier system using coherent Rayleigh backscattered reflectometry," in *Proc. ECOC' 93*, paper MoC1.3, Montreux, Switzerland, Sep. 1993.
[4] W. I. Way and Y. W. Lai, "Effect of transient gain compression in a saturated EDFA on OTDR testing," *Technic. Dig., OFC' 94*, paper WC1, San Jose, Ca., Feb. 1994.
[5] C. R. Giles, E. Desurvire, and J. R. Simpson, "Transient gain and cross talk in erbium-doped fiber amplifiers," *Opt. Lett.*, vol. 14, pp. 880–882, Aug. 1989.
[6] J. Freeman and J. Conradi, "Gain modulation response of erbium-doped fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 224–226, Feb. 1993.
[7] P. J. Keeble, "Optical time domain reflectometry performance enhancement using erbium-doped fiber amplifiers," *SPIE Proc.*, vol. 1366, pp. 39–44, 1990.
[8] Y. K. Chen and S. Chi, "Fault-locating and supervisory technique for multi-staged branced optical networks," to be published in *IEEE Photon. Technol. Lett.*, vol. 6, June 1994.