

# Impulse Response Measurement of Balanced Chains of EDFA's in a Recirculating Loop

L. Potí, A. Bononi, and N. Oriente

**Abstract**—A simple method to measure the small-signal impulse response of balanced chains of both clamped and unclamped erbium-doped fiber amplifiers using a recirculating loop is presented, and the experimental results are checked against theory.

**Index Terms**—Dynamic response, erbium-doped fiber amplifiers, gain control, optical fiber measurement applications, transient response.

## I. THEORY

IT HAS been shown that the speed of gain transients in chains of unstabilized erbium-doped fiber amplifiers (EDFA's) in response to power step variations (channel add/drops) at the chain input increases along the chain, and may reach the submicrosecond range in long chains [1]. Such step response, in the small perturbation regime, can be obtained by integration of the chain impulse response, for which a closed form is known for balanced chains of unstabilized EDFA's [2]. If  $N$  channels at wavelengths  $\lambda_1, \dots, \lambda_N$  and with continuous-wave (CW) input power  $P_1, \dots, P_N$  feed a chain of  $n$  EDFA's at steady state, and if channel  $c$ ,  $1 \leq c \leq N$ , has a power spike variation (ideally a Dirac delta)  $\delta(t)$  at time  $t = 0$ , the power variation at the output of the chain at wavelength  $\lambda_c$  is, for  $t \geq 0$  [2]

$$h_n(t) = \delta(t) + \frac{a_c}{a} \sum_{k=1}^n \binom{n}{k} a^k \left[ \frac{t^{k-1}}{(k-1)!} e^{-t/\tau_o} \right] \quad (1)$$

where  $a \triangleq \sum_{j=1}^N a_j$  and  $a_j \triangleq ((P_j/P_j^{IS})/\tau)(1 - G_j)$ , being  $P_j^{IS}$  and  $G_j$  the intrinsic saturation power and the gain at  $\lambda_j$ , respectively;  $\tau$  is the fluorescence time;  $1/\tau_o = (1/\tau)[1 + \sum_j (P_j/P_j^{IS})G_j]$ , the summation being over pump and signals. This is the impulse response of the unclamped chain.

Gain clamping is a simple yet effective technique to prevent the EDFA gain to swing excessively in response to channel add/drops [3]. Following [2], the impulse response of a balanced chain of  $n$  clamped EDFA's is the same as (1), with the term in square brackets substituted with  $\mathcal{L}^{-1}\{(s/(s^2 + s/\tau_c + \Omega^2))^k\}$ , where  $\mathcal{L}^{-1}$  indicates the inverse Laplace transform, and  $1/\tau_c = 1/\tau_o + (G_l + 1)P_l/P_l^{IS}/2\tau$  (here the index  $l$  indicates the lasing signal with EDFA input power  $P_l$ ), and

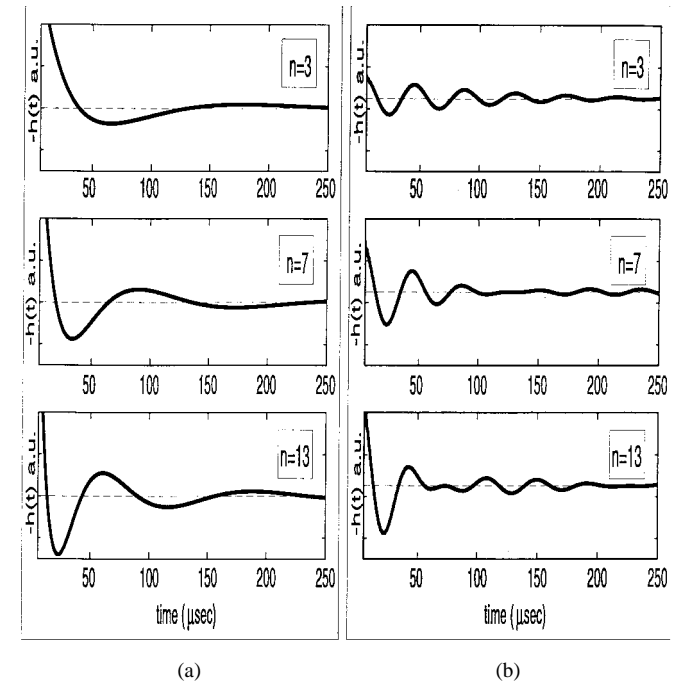


Fig. 1. Chain impulse response to a negative spike. (a) Unclamped. (b) Clamped.  $n$  = number of EDFA's.

$\Omega = \sqrt{(G_l - 1)((P_l/P_l^{IS})/\tau\tau_l)}$  is the relaxation angular frequency;  $\tau_l$  is the clamping loop delay.

Fig. 1 shows the theoretical impulse response  $-h_n(t)$  to a negative delta spike (after subtraction of the delta itself) in chains of  $n = 3, 7, 13$  EDFA's, both (a) unclamped and (b) clamped. In both cases, the impulse response increases in magnitude down the chain. While the impulse response of unclamped EDFA's has more and faster oscillations for increasing  $n$  [2], that in clamped EDFA chains decays faster for increasing  $n$ , but has zero crossings (crossings of the thin dashed line) at the same time locations for all  $n$ 's. After a few tens of amplifiers the main part of  $h(t)$  consists of the first two oscillations, with smaller ripples reappearing at later times.

## II. MEASUREMENTS

We qualitatively tested the above theoretical formulae using a recirculating loop experiment, whose setup is shown in Fig. 2. The procedure is essentially the one used for long-haul signal propagation [4]: the loop is initially charged by a CW signal at  $\lambda_s = 1555$  nm, injected in the loop by an acoustooptic switch (AOM1), while the other switch (AOM2) is OFF. The

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The authors are with the Dipartimento di Ingegneria dell'Informazione, Università di Parma, Viale delle Scienze, I-43100 Parma, Italy.

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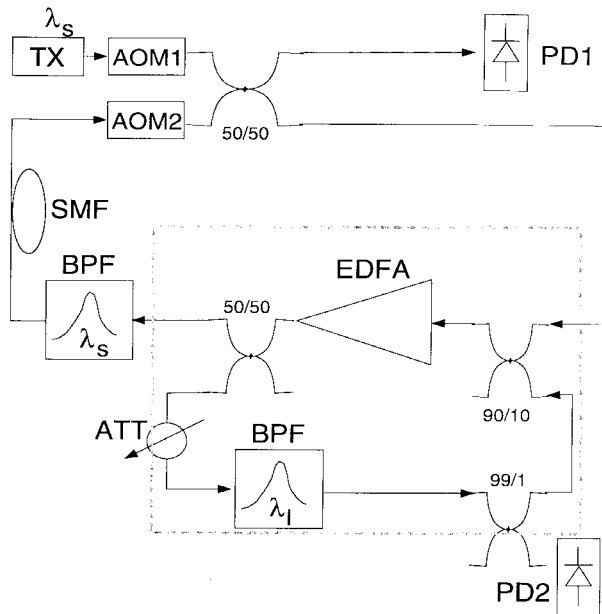


Fig. 2. Recirculating loop experimental setup.

amplifier can be either unclamped (large attenuation in the variable attenuator ATT) or clamped by a lasing signal at  $\lambda_l = 1559.5$  nm (low attenuation in ATT). Clamping has the effect of reducing the gain of the amplifier in order to sustain the laser oscillation. The charge time is long enough to bring the EDFA to steady state.

At time  $t = 0$  AOM1 also goes OFF, and  $\Delta$  seconds later AOM2 goes ON, allowing recirculations in the loop. If  $\Delta$  is much shorter than the EDFA response time, the net effect is to feed the EDFA with a negative Dirac delta, i.e., with a very short dip in the input CW power, which allows to measure the impulse response of the loop.

Consider first the unclamped case. If the delay in the standard single-mode fiber (SMF) is long enough to allow transients to die out, and if the EDFA gain is initially much larger than the loop losses, after a couple of recirculations the EDFA saturates so that its gain at the signal wavelength equals the loop losses. Therefore at each recirculation the average power level at the EDFA input is constant, and the recirculating loop thus correctly emulates the response of a long balanced chain of EDFA's, i.e., one having all EDFA's with the same average inversion. The bandpass filter (BPF) following the EDFA prevents the growth of spontaneous emission at each recirculation in the loop, and allows cleaner measurements of the channel power transients. The fiber length was set to 50 km, giving a recirculation delay of 250  $\mu$ s. At each recirculation the EDFA output is monitored at photodiode PD1.

Fig. 3 shows the measured power of the signal at  $\lambda_s = 1555$  nm at the EDFA output after 3, 7, and 13 recirculations. The negative delta spike causing the transient is barely visible because of the poor sampling of the oscilloscope. What is left is the negative of the impulse response, and should be compared with Fig. 1(a). Although the transients in the initial EDFA's of a straight-line chain are slightly longer than 250  $\mu$ s, as seen in Fig. 1(a), and thus in the loop experiment the EDFA does not exactly reach steady state after each recirculation

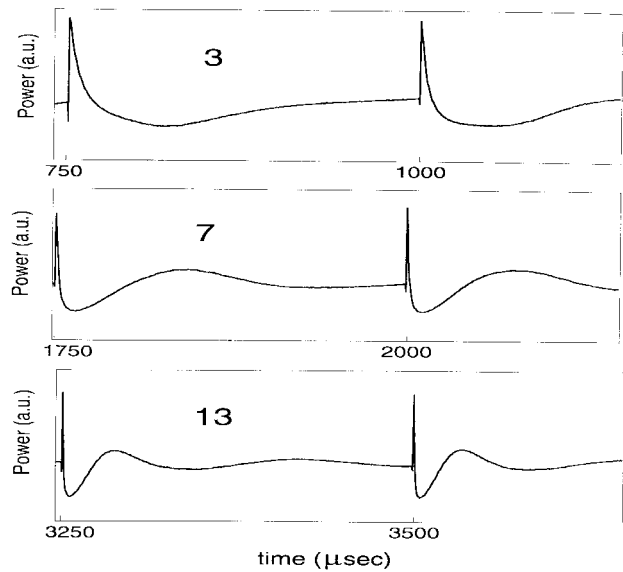


Fig. 3. Measured signal power at output of EDFA in the unclamped case after laps 3, 7, 13.

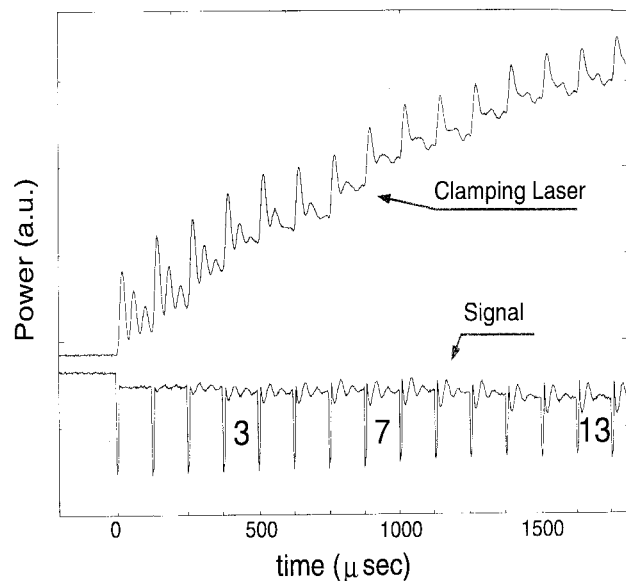


Fig. 4. Measured channel and laser power at output of EDFA in the clamped case for the first 13 recirculations. Power after laps 3, 7, 13 is labeled.

of the perturbation, still there is little discrepancy among the shape and time scales of the theoretical impulse responses of a straight-line chain [Fig. 1(a)] and the measured experimental responses (Fig. 3). We verified that using a longer SMF gives little changes in the measured chain response, although the attenuation is larger and thus the oscilloscope traces are worse.

Consider next the clamped case. As the variable attenuation ATT is reduced, lasing starts and the gain gets clamped. Since the gain is now lower than the loop losses with 50 km of fiber, in order to make the initial gain approach the loop losses (and thus avoid signal fading after a few recirculations) we had to reduce the fiber span to 25 km, giving a recirculation delay of 125  $\mu$ s. Fig. 4 shows the measured EDFA signal output for the first 13 recirculations monitored at PD1 (bottom trace) and the clamping laser (upper trace) monitored at PD2. In this case, the

loop delay was not long enough for transients to die out from one recirculation to the next, and thus the measured results differ a little from those of a straight-line chain of clamped EDFA's. The essence of the impulse response, however, with oscillations crossing the steady state line at regular intervals set by the relaxation frequency, is correctly reproduced.

### III. CONCLUSION

A simple method to measure the impulse response of a long chain of both clamped and unclamped EDFA's has been described. The interesting finding is that while transients in unclamped chains have faster and faster oscillations down the chain, transients in chains of clamped EDFA's keep constant

the steady state power level crossing instants, the dominant part of the response being limited within the first two crossings.

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