Channel Addition–Removal Response in All-Optical Gain-Clamped Lumped Raman Fiber Amplifier

M. Karásek, J. Kaňka, P. Honzátko, and J. Radil

Abstract—**Application of all-optical gain-clamped (AOGC) lumped Raman fiber amplifier (RFA) for protection of surviving channels in multiwavelength networks is investigated experimentally and theoretically. Channel addition–removal was simulated by transmitting signals of two lasers through a counterdirectionally pumped RFA consisting of 16 km of dispersion compensating fiber. Light of one of the lasers was square-wave modulated at 500 Hz; power fluctuations of the other laser caused by cross-gain modulation of the RFA were monitored at the output of the amplifier with a digital oscilloscope. An all-optical feedback loop was implemented in the form of a ring laser. Theoretical analysis of the AOGC lumped RFA is based on numerical solution of coupled propagation equations for forward and backward-propagating pumps, signals, and spectral components of amplified spontaneous emission powers.**

Index Terms—**Cross-gain modulation, power transients, Raman fiber amplifier (RFA), wavelength-division multiplexing.**

I. Introduction

With the development of high-power compact semiconductor laser diode pumps, Raman fiber amplifiers (RFAs) have regained attention as a practical silica-based fiber amplifiers due to their flexible gain band control by changing wavelengths and powers of pump sources. Lumped RFA will play an important role in the next generation of high-speed wavelength-division-multiplexed metropolitan area networks. When the number of channels varies due to channel addition–removal or when burst mode traffic is transmitted in a network where high gain, wide-band lumped RFA are deployed, pump-to-pump and signal-to-signal interactions in RFA may cause power transients that can cause serious service impairments.

Recently, transient effects in RFA have been investigated both theoretically and experimentally, [1]–[5]. Power transients similar to those recorded in erbium-doped fiber amplifiers (EDFAs) have been observed in counterdirectionally pumped saturated RFA and were attributed to depletion of injected pump by the leading edge of signal pulses. Due to the partial pump depletion, the body of the pulse does not enjoy the same high gain as the signal front. Two control schemes widely accepted in EDFAs have so far been suggested and experimentally verified for suppression of power transients in RFA: fast pump power control, [6], [7] and all-optical gain clamping (AOGC), [8], [9]. A proportional-integral-derivative control circuit was implemented in the control scheme demonstrated in [6] to vary the counterdirectional pump power. The control signal was derived either from the surviving channel output power or from both the surviving and the total output power. When the control was OFF, Raman gain fluctuations of the surviving channel ranged from 0.35 to 1.2 dB as the drop/total ratios ranged from 4/8 to 20/24 in the distributed RFA. The control algorithm kept gain fluctuations of surviving channels $<\pm 0.06$ dB. Gain-clamped lumped RFA reported in [9] exhibits a net gain of 22 dB with gain variation of only 0.3 dB for signal input power ranging from -20 to 2.7 dBm. Suppression of power surges during transmission of 500-μs-long optical pulses has been demonstrated.

In this contribution, we extend the experiments presented in [9] by investigating, both experimentally and theoretically, suppression of cross-gain modulation in an AOGC RFA. We transmitted signals from two lasers through 16 km of dispersion compensating fiber (DCF) counterdirectionally pumped at 1430, 1440, and 1450 nm. Light of one of the lasers was 100% square-wave modulated at 500 Hz to simulate channel addition–removal; power fluctuations of the other laser caused by cross-gain modulation of the RFA were monitored at the output of the amplifier with a digital oscilloscope. An all-optical feedback loop was implemented in the form of a ring laser. Theoretical analysis of the AOGC lumped RFA is based on a numerical solution of coupled propagation equations for forward and backward-propagating pumps, signals, and spectral components of amplified spontaneous emission (ASE) powers. Reasonable quantitative agreement between experimental and theoretical results has been achieved.

II. Experimental Setup

Fig. 1 shows our experimental setup. The AOGC RFA, shown in the dashed box, consists of 16 km of DCF, in an OFS EWBDK : 1360 dispersion compensating module, counterdirectionally pumped via circulator by three pumps at 1430, 1440, and 1450 nm and a launched power of 159, 143, and 153 mW, respectively. 30% of the forward propagating ASE generated within the pumped DCF is fed back from the output directional coupler DC_3 via variable attenuator and optical bandpass filter $OBPF_1$ to the 30% port of input directional coupler DC_2. Optical isolator (IS) prevents propagation of backward ASE through the optical feedback loop.

The gain saturation characteristic of the amplifier is plotted in Fig. 2 for unclamped and two different clamped regimes. The gain was measured using the laser tuned at 1538 nm and the

Manuscript received August 29, 2003; revised November 5, 2003. This work was supported in part by the Grant Agency of the Academy of Sciences of the Czech Republic under Project A2067202.

M. Karásek, J. Kaňka, and P. Honzátko are with the Institute of Radio Engineering and Electronics, Academy of Sciences of the Czech Republic, 182 51 Prague, Czech Republic (e-mail: karasek@ure.cas.cz).

J. Radil is with CESNET a.l.e., 160 00 Prague, Czech Republic.

Digital Object Identifier 10.1109/LPT.2004.823727

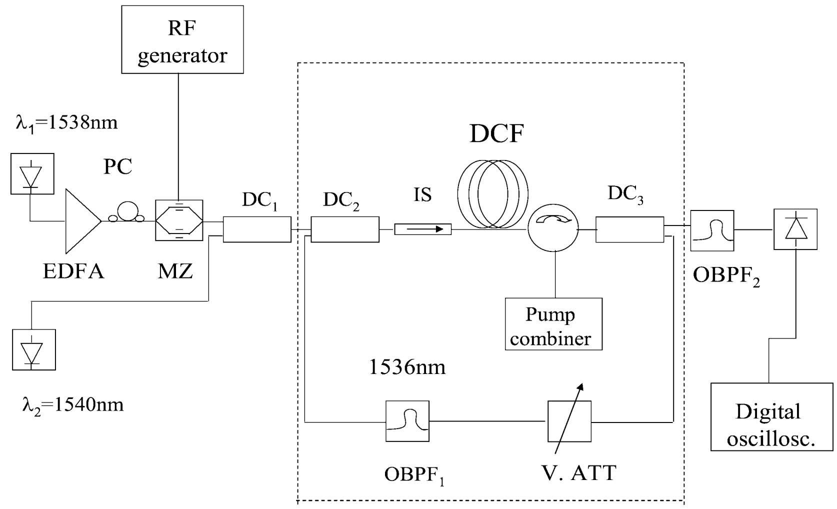

Fig. 1. Experimental setup of AOGC RFA. PC: polarization controller.

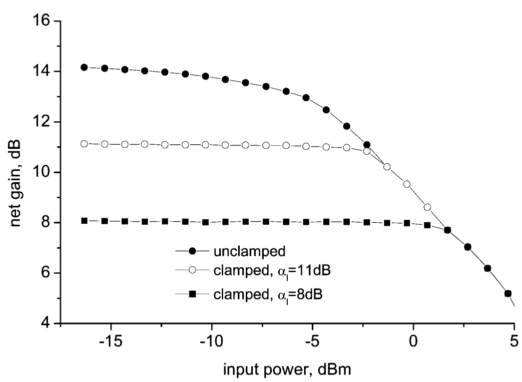

Fig. 2. Single-channel (1538 nm) amplifier gain as a function of input signal power with and without AOGC.

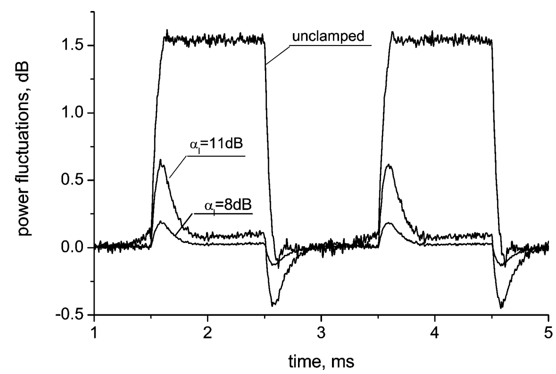

Fig. 3. Output power fluctuations at 1540 nm with and without AOGC. Experiment.

EDFA. The effect of stimulated Brillouin backscattering was suppressed by RF modulation of the electrooptical modulator (MZ). Lasing wavelength has been set to 1536 nm by the tunable bandpass filter OBPF_1. The OBPF_2 was tuned at 1538 nm and the gain measured with power meter. When the optical feedback loop is closed, the gain is clamped to the value equal to loop loss. For the loop loss of $\alpha_l = 8$ dB, variation of net gain is <0.2 dB for signal input power ranging from -17 to $+0.5$ dBm.

In order to investigate the response of AOGC RFA to channel addition–removal, signals from two tunable laser sources were combined in a 3-dB directional coupler DC_1 and injected into the amplifier. Light of the laser tuned to 1538 nm was amplified by EDFA and modulated ON–OFF by a electrooptical modulator to simulate an add–drop regime. RF modulation was superimposed to 500 Hz ON–OFF modulation to suppress the effect of stimulated Brillouin backscattering. The second source at 1540 nm represents the surviving channels. This wavelength was selected from the output spectrum of the AOGC RFA using OBPF_2 and monitored by a digital oscilloscope. Fig. 3 shows two periods of surviving channel power fluctuations for the unclamped and gain-clamped $(\alpha_l = 8, 11 \text{ dB})$ regime. Input powers at 1538 and 1540 nm were -3 and -13 dBm, respectively. Lasing wavelength has beet set at 1536 nm. When the optical feedback loop is disconnected, the steady-state value of the surviving channel power fluctuation is 1.55 dB. In the gain-clamped regime, the fluctuations are suppressed depending on the degree of clamping. For $\alpha_l = 11$, an 8-dB power surge of 0.63 and 0.18 dB has been recorded when the signal at 1538 nm is switched OFF. Similar undershoots appear when the signal is switched ON again (-0.41, -0.11 dB). Steady-state fluctuation is reduced to 0.1 dB when $\alpha_l = 11$ dB and fully eliminated for $\alpha_l = 8$ dB. Surviving channel power fluctuations are eliminated by lasing power variations. When the 1538-nm signal is dropped, more gain is available, the lasing power increases and reaches new steady-state value corresponding to the reduced input signal power. Due to a low power level of the surviving channel at the output of OBPF_2, noise recorded in Fig. 3 represents the noise of the detection system (optical head and the digital oscilloscope).

III. Numerical Simulation

The time-domain model of AOGC RFA used for theoretical analysis of surviving channel fluctuations has been derived from the model described in detail in [7]. Numerical solution to the time-dependent propagation equations starts with the determination of steady-state distributions of pump, signal, and ASE powers along the DCF fiber of length L. The steady-state solution of propagation equations involved in RFA simulation

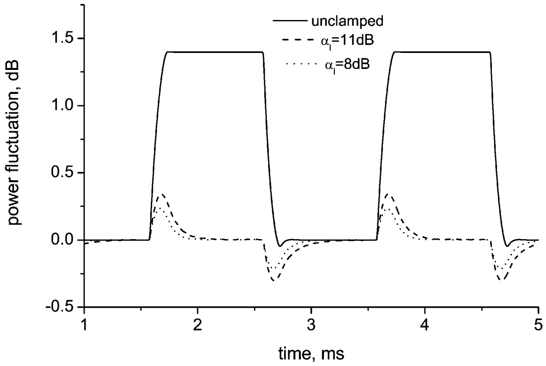

Fig. 4. Output power fluctuations at 1540 nm with and without AOGC. Numerical simulation.

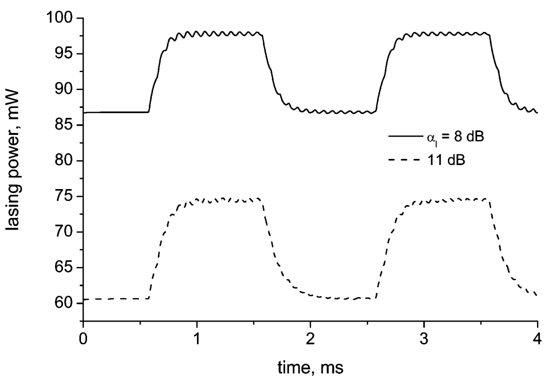

Fig. 5. Time evolution of lasing power at 1536 nm. $\alpha_l = 8, 11$ dB. Numerical simulation.

introduces a two-boundary value problem. Due to the backward-propagating ASE powers and counterdirectional pumping scheme, an iterative forward and backward integration of propagation equations must be used. We applied the fourth-order Runge–Kutta subroutine for these integrations. The optical feedback loop is implemented in the model by modifying the boundary conditions for forward and backward-propagating ASE spectral components by filtering and attenuation–isolation in each iteration cycle. In the following analysis, an OFS EWBDK : 1360 fiber has been considered. Assuming the same input signal and pump wavelengths and powers as in the experiment shown in Fig. 3, we have obtained similar power fluctuations in the surviving channel, both with and without AOGC. Fig. 4 shows the time evolution of power excursions in the surviving channel (1540 nm) at the output of the amplifier for unclamped and two cases of clamped RFA. The steady-state power excursion is 1.40 dB in case of open loop and zero for the clamped RFA. Power overshoots and undershoots for the clamped RFA are slightly lower than those obtained experimentally. Lasing power variations which result in suppression of surviving channel power fluctuations are shown in Fig. 5 for $\alpha_l = 8$ and 11 dB. Simulations of AOGC RFA for other lengths of the Raman fiber proved that the duration of surviving channel power overshoots–undershoots is related to the length of the Raman fiber.

IV. Conclusion

We have demonstrated experimentally and theoretically, for the first time to our knowledge, that AOGC can effectively suppress surviving channel power fluctuations in lumped RFA. In the case where sufficient lasing is allowed, the steady-state fluctuations are fully eliminated. Amplitude of the remaining surviving channel power overshoots–undershoots that occur when channels are switched OFF–ON is about eight times lower than the steady-state power fluctuation of the unclamped RFA. Duration of these power overshoots–undershoots is related to the length of the Raman fiber.

References

[1] C. J. Chen and W. S. Wong, “Transient effects in saturated Raman amplifiers,” *Electron. Lett.*, vol. 37, no. 6, pp. 371–373, 2001.

[2] L. Zhang, S. Wang, and C. Fan, “Transient analysis in discrete fiber Raman amplifiers,” *Opt. Commun.*, vol. 197, pp. 459–465, 2001.

[3] M. Menif, M. Karasek, and L. A. Rusch, “Cross-gain modulation in Raman fiber amplifiers: Experimentation and modeling,” *IEEE Photon. Technol. Lett.*, vol. 14, pp. 1261–1263, Sept. 2002.

[4] A. Bononi and M. Paparo, “Transient gain dynamics in saturated counter-pumped Raman amplifiers,” in *Proc. Optical Fiber Communications (OFC 2002)*, Anaheim, CA, 2002, Paper ThR1, pp. 511–512.

[5] S. Wang, L. Zhang, Z. Jiang, J. Wang, and C. Fan, “Abrupt and asymptotic transience in DWDM systems using backward-pumped fiber Raman amplifier,” *IEEE Photon. Technol. Lett.*, vol. 14, pp. 1264–1266, Sept. 2002.

[6] C. J. Chen, J. Ye, W. S. Wong, Y. W. Lu, M. C. Ho, Y. Cao, M. J. Gassner, J. S. Pease, H. S. Tsai, H. K. Lee, S. Cabot, and Y. Sun, “Control of transient effects in distributed and lumped Raman amplifiers,” *Electron. Lett.*, vol. 37, no. 21, pp. 1304–1305, 2001.

[7] M. Karasek and M. Menif, “Protection of surviving channels in pump-controlled gain-locked Raman fiber amplifier,” *Opt. Commun.*, vol. 210, pp. 57–65, 2002.

[8] X. Zhou, H. H. M. Shalaby, C. Lu, P. Shum, and T. Cheng, “Theoretical investigation of fiber Raman amplifier with dynamic gain control,” in *Proc. Optical Fiber Communications (OFC 2001)*, Anaheim, CA, 2001, Paper WDD17-1.

[9] S. S.-H. Yam, F.-T. An, E. S.-T. Hu, M. E. Marhic, T. Sakamoto, L. G. Kazovsky, and Y. Akasaka, “Gain-clamped S-band discrete Raman amplifier,” in *Proc. Optical Fiber Communications (OFC 2002)*, Anaheim, CA, 2002, Paper ThB4, pp. 385–387.