# Semianalytic Dynamic Gain-Clamping Method for the Fiber Raman Amplifier

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***Abstract*—We present a physically meaningful semianalytic gain-clamping algorithm for multipump Raman fiber amplifier in large signal regime. By utilizing parameters from the steady state conditions, the suppression of gain excursion below 0.5 dB (up to 78/80 channel drop) can be achieved within microsecond/millisecond time scale, depending on the signal power level.**

***Index Terms*—Algorithms, gain control, optical fiber amplifiers, transient response.**

## I. Introduction

FOR THE future optical link equipped with dynamic lambda channel routing function, there have been many efforts to develop an efficient control method for a fiber Raman amplifier (FRA) to cope with possible wavelength-division-multiplexing channel add–drop. For the purpose of assessing the issues related with FRA transient, such as cross-gain modulation, signal stimulated Raman scattering (SSRS), and pump-to-pump interaction, numerical and experimental studies have been carried out [1]–[3]. Even if the gain-control method based on pump grouping [4], amplified spontaneous emission/gain slope measurement [5], pump optical time-domain reflectometer [6], linear matrix [7], or closed-form FRA equation [8] have provided some insights/resolutions to keep constant signal gain under dynamic channel add–drop, still a fast clear algorithm dedicated for the dynamic gain clamping applicable to wide-band FRA with a large number of multipump–signal have not been proposed, especially in large signal regime where pump depletion/SSRS effects manifest.

In this work, we present a semianalytic algorithm for the calculation of proper pump powers required to keep constant gain profile, for surviving channels under dynamic add–drop reconfiguration environment. Using parameters from the FRA in steady state (Raman coefficient, attenuation spectrum, information on total/surviving channel) [6], we demonstrate (as an application example) that the gain excursion of distributed FRA in large signal regime with 100-km single-mode fiber (SMF) can be suppressed below 0.5 dB with reasonable processing time, over the whole gain bandwidth of 70 nm and arbitrary choice of channel drop-out (up to 78/80 channel drop and +5 dBm/channel).

Manuscript received October 18, 2004; revised December 10, 2004. This work was supported by the Ministry of Science and Technology of Korea through the National Research Laboratory Program.

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Digital Object Identifier 10.1109/LPT.2005.843688

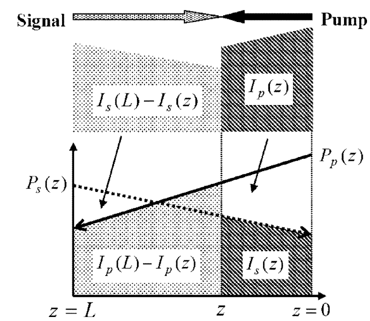


Fig. 1. Integrals of signal–pump power (illustrated as area) for an backward-pumped FRA (solid–dotted line: evolution of pump–signal).

## II. Formulation/Algorithm

Separating pump and signal part, the gain of FRA with $M$ pumps and $N$ signals can be written in the following form:

$$\begin{bmatrix} G_p \\ G_s \end{bmatrix} = \begin{bmatrix} C_{pp} & C_{sp} \\ C_{ps} & C_{ss} \end{bmatrix} \begin{bmatrix} I_p \\ I_s \end{bmatrix} \tag{1}$$

where $G_p$ ($G_s$) are $M \times 1$ ($N \times 1$) vector representing the Raman gain for pumps (signals), and $I_p$ ($I_s$) is the vector constructed from the power integral of pumps (signals). To note, the $\exp(G_p)$ and $\exp(G_s)$ are the exact Raman gain in linear scale. $C_{pp}$, $C_{sp}$, $C_{ps}$, and $C_{ss}$ are the matrix size of $M \times M$, $M \times N$, $N \times M$, and $N \times N$ constructed by Raman gain coefficient. Taking the pump input end as $z = 0$ (as in Fig. 1), the integrals of signal (starting from $z = L$) and pump power can be related to their boundary condition as follows:

$$G_p(z) = C_{pp}I_p(z) + C_{sp}I_s(z) \tag{2}$$
$$G_s(z) = C_{ps}\{I_p(L) - I_p(z)\} + C_{ss}\{I_s(L) - I_s(z)\}. \tag{3}$$

Assuming a channel reconfiguration, note that then the following equations must be satisfied, if one wants to keep the gain of surviving channels unchanged. Taking the differentials of (3) and by setting $z = 0$ we get

$$\Delta G_s(0) = C_{ps}\Delta I_p(L) + C_{ss}\Delta I_s(L) = 0 \tag{4}$$
$$\Delta I_p(L) = -(C_{ps})^{-1}C_{ss}\Delta I_s(L) \tag{5}$$

where $\Delta G_s$, $\Delta I_s$ ($\Delta I_p$) are the differential changes in the signal gain/integral of signal (pump) power. Differentiating (2) and (3), then substituting the result of (4), we get the distribution of pump–signal wave differential gain

$$\Delta G_p(z) = C_{pp}\Delta I_p(z) + C_{sp}\Delta I_s(z) \tag{6}$$
$$\Delta G_s(z) = -C_{ps}\Delta I_p(z) - C_{ss}\Delta I_s(z). \tag{7}$$

On the other hand, we use the definition of effective length to relate the differential of pump power integral $\Delta I_p$ to the differential of input pump power $\Delta P_p(0)$ (note that is this the final target solution) as follows:

$$\begin{aligned} L_{\mathrm{eff},p}(z)+\Delta L_{\mathrm{eff},p}(z) &= \frac{\int_0^z P_p(\zeta)+\Delta P_p(\zeta)d\zeta}{P_p(0)+\Delta P_p(0)} \\ &= \frac{I_p(z)+\Delta I_p(z)}{P_p(0)+\Delta P_p(0)} \qquad (8)\\ \therefore \Delta P_p(0) &= \frac{\Delta I_p(z)-\Delta L_{\mathrm{eff},p}(z)P_p(0)}{L_{\mathrm{eff},p}(z)+\Delta L_{\mathrm{eff},p}} \\ & (\because I_p(z)=L_{\mathrm{eff},p}(z)\cdot P_p(0)). \qquad (9)\end{aligned}$$

To get the final target solution $\Delta P_p(0)$ at different orders of approximation (equivalently, at different levels of signal power), we start from the small signal regime.

### A. Stage I. Small Signal: Zeroth-Order Approximation

Assuming small signal (undepleted pump approximation), the evolution curves of surviving channels after the channel reconfiguration should be equal to those of steady state. In this case, $\Delta I_s^{(0)}(z)$ of surviving channels are zero, and those of dropped channels are $I_s(z)$ naturally.

As we can ignore the pump depletion effects, we set $\Delta L_{\mathrm{eff},p}^{(0)}(z) = 0$ in (9) to get zeroth-order solution of $\Delta P_p^{(0)}(0) = \Delta I_p(L)/L_{\mathrm{eff},p}(L)$, meanwhile using (5) to get $\Delta I_P(L)$ from the known values of $\Delta I_s^{(0)}(z)$.

### B. Stage II. Large Signal: First-Order Approximation

Further extending the formalism to enable the calculation of $\Delta P_p(0)$ in the large signal domain, we need to provide reasonable nonzero estimation for $\Delta L_{\mathrm{eff},p}(z)$ and $\Delta I_s(z)$, which were treated as zero in Stage I. At first, we calculate the evolution of differential pump integral, at zeroth-order approximation, $\Delta I_p^{(0)}(z) = \Delta P_p^{(0)}(0)L_{\mathrm{eff},p}(z)$ by using the values of $\Delta P_p^{(0)}(0)$ obtained in Stage I. Now applying $\Delta I_p^{(0)}(z)$ and $\Delta I_s^{(0)}(z)$ into (6) to get $\Delta G_p(z)$, the value of $\Delta I_p(z)$ in first-order approximation can be calculated as shown in (10) at the bottom of the page.

Likewise, substituting $\Delta I_p(z)$ and $\Delta I_s^{(0)}(z)$ into (7) to get $\Delta G_s(z)$, and remembering that $\Delta P_s(0)$ equals zero for the surviving channel, a differential of the signal integral value $\Delta I_s(z)$ in first-order approximation can be calculated as shown in (11) at the bottom of the page.

Finally, we use $\Delta I_p(z)$ and $\Delta I_s(z)$ to get the differential of pump effective length $\Delta L_{\mathrm{eff},p}(L)$ from the following equation:

$$\begin{aligned}\Delta L_{\mathrm{eff},p}(L) &= -L_{\mathrm{eff},p}(L) \\ &+\int_0^L \exp\{-\alpha_p z+G_p(z)+(C_{pp}\Delta I_p(z)+C_{sp}\Delta I_s(z))\}dz \end{aligned} \qquad (12)$$

to be substituted in (9) (with $\Delta I_P(L)$ from Stage I) to get the final solution of $\Delta P_p(0)$ in first-order approximation.

### C. Stage III. Semianalytic Correction

Though the algorithm described in Stage II can provide a quite accurate solution in large signal regime, still even more precise solution can be obtained with the introduction of a semiempirical error correction method. With a one-time reference measurement for the *remaining* gain error $\delta G_s(0)_{\mathrm{REF}}$ (after the application of algorithm stated in Stage II), we calculate the correction factor $\delta I_p(L)_{\mathrm{REF}} = -(C_{ps})^{-1}\delta G_s(0)_{\mathrm{REF}}$ from (7), neglecting $\delta I_s(z)$ ($\ll \delta I_p(z)$). From this, without any further measurement, we can derive the correction factor applicable to arbitrary numbers of dropping channel $N$, from the scaling of channel number: $\delta I_p(L)_N = \delta I_p(L)_{\mathrm{REF}}(N/N_{\mathrm{REF}})$, where $N_{\mathrm{REF}}$ is the number of dropping channel in the reference measurement. Finally, we calculate the semiempirically error-corrected solution $\Delta P_p^*(0)$ from (9) with $\Delta I_p^*(L) = \Delta I_p(L) + \delta I_p(L)$.

## III. Application Example

To verify the *robustness/effectiveness* of the proposed algorithm, numerical analysis has been carried out in large signal regime. Forty signal waves with 100-GHz spacing, for each of *C*/*L*-band (+5 dBm/ch, total 24 dBm) have been assumed. Fourteen backward propagating pumps (1420 $\sim$ 1480 nm with 5-nm spacing, and 1495 nm) were used to provide 10 dB of on–off gain for 100 km of SMF. The used pump powers were 191.2, 101.3, 79.4, 101.8, 49.6, 32.5, 41.7, 14.7, 18.8, 30.5, 15.7, 19.5, 18.0, and 21.9 mW (in the order of increasing wavelength), respectively. Comparing the total input signal power (250 mW) to total pump power (736.3 mW), the pump depletion effect in the FRA is evident. Fig. 2 shows the gain spectrum of FRA with/without feedback, for different channel reconfiguration scenarios: (A) interleaving, distributed channel drop, and (B) red/blue band channel drop. The solid line shows the gain spectrum in steady-state before the channel reconfiguration. The dashed line also shows the gain-excursion spectrum without the

$$\Delta I_p(z) = -I_p(z) + \int_0^z \left\{P_p(0)+\Delta P_p^{(0)}(0)\right\}\exp\left\{-\alpha_p\zeta+G_p(\zeta)+\left(C_{pp}\Delta I_p^{(0)}(\zeta)+C_{sp}\Delta I_s^{(0)}(\zeta)\right)\right\}d\zeta \qquad (10)$$

$$\Delta I_s(z) = -I_s(z) + \int_0^z \{P_s(0)+\Delta P_s(0)\}\exp\left\{-\alpha_s\zeta+G_s(\zeta)+\left(-C_{ps}\Delta I_p(\zeta)-C_{ss}\Delta I_s^{(0)}(\zeta)\right)\right\}d\zeta \qquad (11)$$

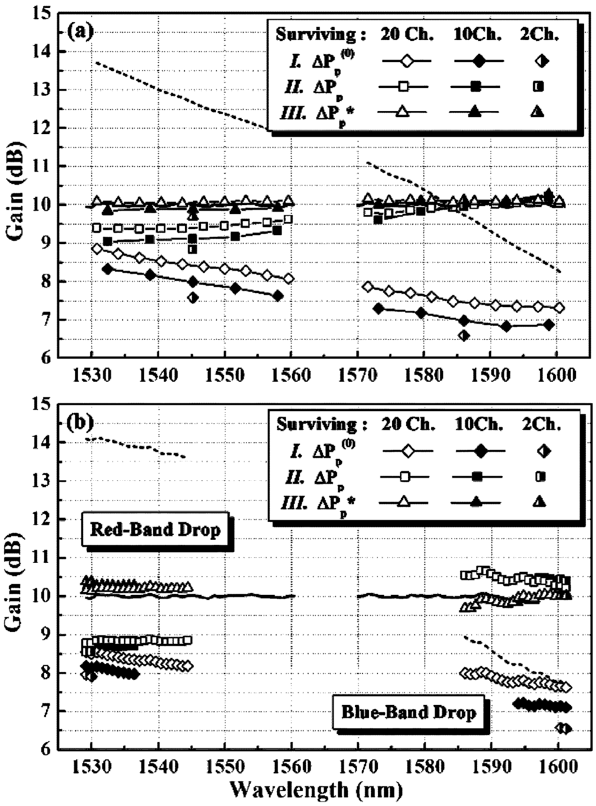


Fig. 2. Gain-excursion spectrum with/without the pump control, at different stages of algorithm (I, II, III) for (a) Scenario A, (b) Scenario B.

gain control, after 9 dB of channel count reduction (60 channel drop, out of 80). Without control, as much as 5 dB of gain excursion have been observed after 16 dB of channel count reduction (78 out of 80 channel drop). To compare, we plot the result of gain control at different stages of approximation: I) $\Delta P_p^{(0)}$; II) $\Delta P_p$; and III) $\Delta P_p^*$. As can be seen, the reduction in the gain error is evident along the expansion of algorithm from the small signal to large signal regime. With the proposed semianalytic correction algorithm (described in Stage III), the residual gain error was suppressed below 0.5 dB over the whole gain bandwidth, up to 16-dB channel count reduction. Note that, as mentioned previously, the result of one reference measurement for $\delta I_p(L)_{\mathrm{REF}}$ (for this example, taken at 6 dB of channel reduction, $N_{\mathrm{REF}} = 20$) was enough to provide the precise estimation of required pump power adjustment for all of the other dropping-channel counts up to 78/80 ch.

It is worth noting, in principle, that Scenario A is equivalent to the simple input signal power change for all of the channels. For this case, we observed the linear dependence for the pump power to the number of channels (Fig. 3), consistent with previous reports [5], [7]. However, for the case of band add–drop (Scenario B), significant deviation from the linearity was observed, especially in large signal regime.

Furthermore, we would like to also note that this semianalytic approach does not require any time-consuming process such as solving a differential equation to find the solution. Rather, with several steps of straightforward calculation using the predetermined parameters of FRA in steady states, the search for adjusted pump powers can be carried out much faster, tens of microseconds for approximations up to Stage I, and a few milliseconds for Stages II and III with 2-GHz PC, when compared to the fastest general solution search method (seconds) [8]. For the moderate input signal level (0 dBm $\times$ 80 ch), the analytic solution $\Delta P_p$ from Stage II was enough to suppress the gain error below 0.5 dB. For the small input signal ($-10$ dBm $\times$ 80 ch), the simplest but fastest analytic solution $\Delta P_p^{(0)}$ (using approximation up to Stage I) was enough to achieve same level of clamping performances.

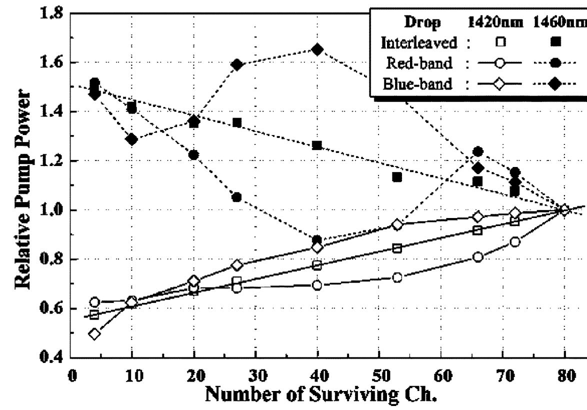


Fig. 3. Adjusted pump powers (normalized) as a function of surviving channels, for different channel add–drop scenarios.

## IV. Conclusion

We have proposed a semianalytic gain-control algorithm for the FRA under channel add–drop environment. The accuracies of control algorithm at different stages in the approximation have been investigated with FRA in large signal regime. Highly accurate (<0.5 dB) fast (tens of microseconds to milliseconds) control of multichannel gain over 70-nm bandwidth with large dynamic range (16 dB) have been demonstrated.

## References

[1] S. Gray, "Transient gain dynamics in wide bandwidth descrete Raman amplifiers," in *Proc. Optical Fiber Communication (OFC 2002)*, 2002, Paper ThR2, pp. 512–513.

[2] M. Karasek, J. Kanka, P. Honzatko, and P. Peterka, "Modeling of a pump-power-controlled gain-locking system for multi-pump wideband Raman fiber amplifiers," in *Proc. Inst. Elect. Eng., Optoelectronics*, vol. 151, 2004, pp. 74–80.

[3] A. Bononi and M. Fuochi, "Transient gain dynamics in saturated Raman amplifiers with multiple counter-propagating pumps," in *Proc. Optical Fiber Communication (OFC 2003)*, 2003, Paper ThC3, pp. 439–441.

[4] Y. Emori, S. Kado, and S. Namiki, "Simple gain control method for broadband Raman amplifiers gain-flattened by multi-wavelength pumping," in *Proc. Eur. Conf. Optical Communication (ECOC 2001)*, 2001, Paper Tu.A.2.2, pp. 158–159.

[5] M. Sobe and Y. Yano, "Automatic pump power adjustment for gain-flattened multi-wavelength pumped Raman amplifier," in *Proc. Optical Fiber Communication (OFC 2002)*, 2002, Paper TuJ5, pp. 63–65.

[6] P. Kim, J. Park, H. Yoon, J. Park, and N. Park, "*In situ* design method for multichannel gain of distributed Raman amplifier with multiwave OTDR," *IEEE Photon. Technol. Lett.*, vol. 14, no. 12, pp. 1683–1685, Dec. 2002.

[7] W. Zhang, X. Feng, J. Peng, and X. Liu, "A simple algorithm for gain spectrum adjustment of backward-pumped distributed fiber Raman amplifiers," *IEEE Photon. Technol. Lett.*, vol. 16, no. 1, pp. 69–71, Jan. 2004.

[8] J. Park, P. Kim, J. Park, H. Lee, and N. Park, "Closed integral form expansion of Raman equation for efficient gain optimization process," *IEEE Photon. Technol. Lett.*, vol. 16, no. 7, pp. 1649–1651, Jul. 2004.