Semi-Analytic Gain Control Algorithm for the Fiber Raman Amplifier under Dynamic Channel Reconfiguration

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Abstract: A semi-analytic gain-clamping algorithm for the deeply saturated, multi-pump fiber Raman amplifier (FRA) is proposed. Utilizing parameters from the steady state conditions, the gain excursion below 0.5dB (up to 78/80 channel drop, +5dBm/channel) can be achieved within milliseconds time scale.

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I. Introduction

With technological advancement for the future optical link equipped with dynamic lambda channel routing function, there have been many efforts to develop the control method for an FRA (fiber Raman amplifier) to cope with input power variation induced by WDM channel add/drop. To assess the FRA-transient related issues such as cross gain modulation, SSRS (Signal Stimulated Raman Scattering), and pump-to-pump interaction, numerical and experimental studies have been carried out [1-3]. Though the gain control method based on pump grouping [4], ASE / gain slope measurement [5, 6] or linear matrix method [7], closed form expansion [8] could provide some clues for the algorithm keeping constant gain values under channel add/drop condition, still a clear algorithm have not been proposed, especially in deep saturation regime where pump depletion / SSRS effects manifest.

In this work, we present a semi-analytic algorithm for the calculation of proper pump powers required to keep constant gain profile, for surviving channels under the dynamic add/drop reconfiguration environment. Using parameters obtained from the FRA in two operation point of steady state, we show that the gain excursion of deeply-saturated, distributed FRA with 100km SMF can be suppressed within 0.5dB over the whole gain bandwidth of 70nm, for arbitrary numbers of channel drop out (up to 78/80 channel drop, 5dBm/ch).

II. Formulation / Algorithm

The gain of FRA with \( M \) pumps and \( N \) signals can be written in the following form, separating pump and signal part.

\[
\begin{bmatrix}
G_p \\
G_s
\end{bmatrix} =
\begin{bmatrix}
C_{pp} & C_{sp} \\
C_{ps} & C_{ss}
\end{bmatrix}
\begin{bmatrix}
I_p \\
I_s
\end{bmatrix}
\]

(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). Under this formulation, the physical meanings of the sub-matrix \( C \) becomes clear: \( C_{pp} = \) pump-to-pump, \( C_{ss} = \) signal-to-signal (signal SRS), \( C_{sp} = \) signal-to-pump (pump depletion), and \( C_{ps} = \) pump-to-signal (signal amplification) interaction. Taking the pump input end as \( z = 0 \), the integrals of signal (starting from \( z = L \)) and pump power can be related with their boundary condition as;

\[
G_p(z) = C_{pp}I_p(z) + C_{sp}I_s(z)
\]

(2)

\[
G_s(z) = C_{ps}\{I_p(L) - I_p(z)\} + C_{ss}\{I_s(L) - I_s(z)\}
\]

(3)

Note that then the following equations must be satisfied, if one wants to keep gain of surviving channel unchanged under the channel reconfiguration environment. Taking differential of equation (3) and setting \( z = 0 \) we get,

\[
\Delta G_s(0) = C_{ps}\Delta I_p(L) + C_{ss}\Delta I_s(L) = 0 \quad \Rightarrow \Delta I_{p,s}(z = 0) = \int_0^L P_{p,s}(z')dz' = 0
\]

(4)

\[
\Delta I_p(L) = -C_{ps}^{-1}C_{ss}\Delta I_s(L)
\]

(5)

where, \( \Delta G_s \), \( \Delta I_p \), and \( \Delta I_s \) are the changes (differentials) in the signal gain, the integral of signal and integral of pump power. For initial approximation (will be corrected later) we assume that the evolution of surviving channel to be equal to that of steady state (un-depleted approximation), to get the initial guess \( \Delta I_{s}^{(0)}(L) \) and \( \Delta I_{s}^{(0)}(z) \). For this, \( \Delta I_{s}^{(0)}(z) \) of surviving channels are zero, meanwhile those of dropped channels are naturally - \( I_s(z) \).

By applying equation (4) into equation (3), we now get the distribution of signal wave differential gain (equation 7);
\[ \Delta G_p(z) = C_{pp} \Delta I_p(z) + C_{sp} \Delta I_s(z) \]  
\[ \Delta G_s(z) = -C_{ps} \Delta I_p(z) - C_{ss} \Delta I_s(z) \]  
\[ \Delta G_r(z) = \Delta G_p(z) + \Delta G_s(z) \]

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 this is the final target solution - as follows.

\[ L_{eff,p} + \Delta L_{eff,p} = \int_0^L \frac{P_p(z) + \Delta P_p(z) dz}{P_p(0) + \Delta P_p(0)} = \frac{I_p(L) + \int P_p(L) dz}{P_p(0) + \Delta P_p(0)} \]  
\[ \therefore \Delta P_p(0) = \frac{\Delta I_p(L) - \Delta L_{eff,p} P_p(0)}{L_{eff,p} + \Delta L_{eff,p}} \]  
\[ \Delta I_p(z) = \Delta P_p(0) L_{eff,p}(z) \]  
\[ \Delta I_s(z) = -I_s(z) + \int_0^z P_s(0) + \Delta P_s(0) \exp \left\{ \alpha_p z + G_p(z) + \left( C_{pp} \Delta I_p(z) + C_{sp} \Delta I_s(z) \right) \right\} dz \]  
\[ \Delta I_r(z) = \Delta I_p(z) + \Delta I_s(z) \]

Even if we do not have any information about \( \Delta L_{eff,p} \) at this stage, under the un-depleted pump assumption which we used before, we can set \( \Delta L_{eff,p} \) as zero [7] in equation (9) to get the initial approximation of \( \Delta P_p(0) \).

At the same time, the \( \Delta I_p(L) \) can be calculated from equation (5) using \( \Delta I_r(0) \). Specifically, we set the initial approximation of \( \Delta P_p(0) \) as \( \Delta P_p(0) = \Delta I_p(L) / L_{eff,p} \).

Further extending the algorithm to enable the calculation of \( \Delta P_p(0) \) in the large signal domain, we need to provide reasonable estimation for \( \Delta L_{eff,p} \) and \( \Delta I_p(z) \) - which were treated as zero in the un-depleted approximation. For this purpose, we substitute the initial approximation of \( \Delta P_p(0) = \Delta I_p(L) / L_{eff,p} \) and \( \Delta L_{eff,p}=0 \) into equation (8), obtaining the un-depleted approximation of \( \Delta I_p(z) \);

\[ \Delta I_p^{(0)}(z) = \Delta P_p^{(0)}(0) L_{eff,p}(z) \]

Applying the result of equation (10) into equation (6) to get \( \Delta G_p(z) \), together with the previously obtained value of \( \Delta P_p^{(0)}(0) \), a differential of the pump integral \( \Delta I_p(z) \) now can be calculated from the following equation (11).

\[ \Delta I_p(z) = \int_0^z P_p(0) + \Delta P_p(0) \exp \left\{ \alpha_p z + G_p(z) + \left( C_{pp} \Delta I_p(z) + C_{sp} \Delta I_s(z) \right) \right\} dz \]  
\[ \Delta I_s(z) = -I_s(z) + \int_0^z P_s(0) + \Delta P_s(0) \exp \left\{ \alpha_s z + G_s(z) + \left( -C_{ps} \Delta I_p(z) - C_{ss} \Delta I_s(z) \right) \right\} dz \]  
\[ \Delta I_r(z) = \Delta I_p(z) + \Delta I_s(z) \]

Note that in equation (11), \( C_{pp} \Delta I_p(z) \) represents the contribution to differential pump gain \( \Delta G_p(z) \) from the change of pump interaction effect, and \( C_{sp} \Delta I_s(z) \) represents the contribution from the change of pump depletion effect after the channel reconfiguration.

Likewise, using the result of equation (11) into equation (7) to get \( \Delta G_s(z) \), along with the previously determined initial approximation of \( \Delta I_r(0) \), and reminding that \( \Delta P_p(0) \) equals to zero for the surviving channel, a differential of the signal integral value \( \Delta I_s(z) \) can be calculated as follows.

\[ \Delta I_p(z) = -I_p(z) + \int_0^z P_p(0) + \Delta P_p(0) \exp \left\{ \alpha_p z + G_p(z) + \left( C_{pp} \Delta I_p(z) + C_{sp} \Delta I_s(z) \right) \right\} dz \]  
\[ \Delta I_s(z) = -I_s(z) + \int_0^z P_s(0) + \Delta P_s(0) \exp \left\{ \alpha_s z + G_s(z) + \left( -C_{ps} \Delta I_p(z) - C_{ss} \Delta I_s(z) \right) \right\} dz \]  
\[ \Delta I_r(z) = \Delta I_p(z) + \Delta I_s(z) \]

Note that in equation (12), \( C_{ps} \Delta I_p(z) \) represents the contribution to differential signal gain \( \Delta G_s(z) \) from the change of signal interaction (SRS) effect, and \( C_{sp} \Delta I_s(z) \) represents the contribution from the change of signal amplification.

Finally, using the definition of effective length and taking its differential, we use equation (6) with the result of equation (11) and (12) to get the differential of pump effective length \( \Delta L_{eff,p} \);

\[ \Delta L_{eff,p}(L) = -L_{eff,p}(L) + \int_0^L \exp \left\{ \alpha_p z + G_p(z) \right\} \exp \left\{ C_{pp} \Delta I_p(z) + C_{sp} \Delta I_s(z) \right\} dz \]  
\[ \therefore \Delta I_p(L) = \Delta L_{eff,p}(L) + \Delta I_p(L) \]

to be used in equation (9) to get the final target solution of differential pump power at the end, \( \Delta P_p(0) \).

Still, even more precise control can be obtained by introducing a semi-empirical error correction factor \( \delta I_p(L) \), to compensate the remaining gain error \( \delta G_p(0) \) - obtained from the measurement after the application of the algorithm down to equation (13). Neglecting the effect of \( \Delta I_s(z) \) (\( \ll \Delta I_p(z) \)), we first solve for \( \delta I_p(L) \) from \( \delta G_p(0) \) using equation (6) (\( \delta I_p(L) = [C_{pp}]^{-1} \delta G_p(0) \)), and then calculate the semi-empirically error-corrected solution \( \Delta P_p(0) \), by applying \( \Delta I_p^c(L) = \Delta I_p(L) + \delta I_p(L) \) to the equation (9). It is important to note that, once the reference measurements are made to get \( \delta G_p(0)_{REF} \) and \( \delta I_p(L)_{REF} \), the result can be directly applied to other numbers of dropping channels (\( N \)) without the need of further measurement, following the power-rescale procedure to obtain \( \delta I_p(L)_N = \delta I_p(L)_{REF} (N/N_{REF}) \), where \( N_{REF} \) is the number of dropping channel in the reference measurement.

III. Application Example

To verify the robustness of the algorithm, test has been carried out in the deep saturation regime. 40 signal waves with 100GHz spacing for each of C / L-Band, at the input signal power +5dBm/Ch (total 24dBm) has been prepared.
14 backward propagating pumps (1420nm ~ 1480nm with 5nm spacing, and 1495nm) were used to provide 10dB (solid line in Fig. 1, 2) of on-off gain for a 100km of SMF. The used pump powers in the simulation 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 21.9mW (in the order of increasing wavelength) respectively. Comparing the total input signal power (250mW) to the total pump power (736.3mW), the pump depletion effect in the FRA is evident. Figure 1 and 2 shows the gain spectrum of FRA with / without feedback for different cases of channel reconfiguration scenario ; A = interleaving, distributed channel drop, and B = (red / blue) band channel drop. Worth to mention, in principle, scenario A is equivalent to the simple signal power change for all the channels. The dashed line shows the gain excursion without control after the 9dB of channel count reduction (60 channel drop, out of 80). Without control, as much as 5dB of surviving-channel gain excursion have been observed after 16dB of channel count reduction (78 out of 80 channel drop). To compare, we also plot the result of gain control at different stages of approximations ($\Delta P_p^{(0)}$, $\Delta P_p$, and $\Delta P_p^*$. As can be seen, the reduction in the gain error is evident, as we increase the orders of approximation. With the proposed semi-analytic algorithm, the residual gain error was suppressed below 0.5dB over the whole gain bandwidth up to 16dB of channel count reduction. Note that, as mentioned previously, the result of one reference measurement for $\delta I_p(L)_{REF}$ (taken at 6dB of channel count reduction) was enough to provide the precise estimation of required adjustment in the pump power, for all of the other dropping-channel counts. As this semi-analytic approach does not require any time consuming process such as solving differential equation but only involves simple calculation using the measured parameters of FRA in steady-states, the whole procedure for the search of adjusted pump powers can be carried out much faster (~ms with 2GHz PC) than the case of general solution search algorithm (sub-second) [8].

IV. Conclusion

We presented a physically meaningful, semi-analytic algorithm for the gain control of a FRA. The accuracies of gain control at different stages of approximation have been investigated with a deeply saturated amplifier. We also showed that highly accurate (<0.5dB), fast (~ms) control of multi-channel gain, over wide dynamic range (16dB) of signal power could be achieved with pre-measured, steady-state FRA parameters at the time of installation.

References


Figure 1. For scenario A, un-controlled / controlled gain spectrum at different stages of approximation with different surviving Ch.

Figure 2. For scenario B, un-controlled / controlled gain spectrum at different stages of approximation with different surviving Ch.