ThR 2:00 pm–3:30 pm

Ballroom B

Amplifier Transient Dynamics

William Shieh, *Dorsal Networks, Inc., USA, Presider*

ThR1 2:00 pm

Transient Gain Dynamics in Saturated Counter-pumped Raman Amplifiers

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Transient gain dynamics in doped-fiber amplifiers have been studied intensively in connection with sudden channel addition or removal caused by either unintentional failures, or by deliberate network reconfigurations.[1,2] The main concern here is in the duration of the power transients, which may induce temporary performance degradation, and the amount of power surges, which may damage the optical components and cause system disruption. Such transients are connected to the population dynamics of the dopant ions, and can be much faster than the ions relaxation time, depending on the signals saturating power.[2–4]

Surprisingly, such gain transients have recently been shown to exist even in counter-pumped saturated Raman amplifiers,[5] where no ions are involved in the amplification process. The reason is that the strong power of the signal leading edge at the amplifier output depletes the injected pump, and thus the main body of the signal pulse does not enjoy the same high gain as the signal front. In this paper, we show that the gain dynamics are completely determined by the time behavior of a single state variable, namely the relative pump change sensed by the signals.

Model

The propagation equations for signals and pump that we consider are the following:

$$\begin{cases} \left(\frac{\partial}{\partial z}+\frac{1}{\upsilon}\frac{\partial}{\partial t}\right)S_j(t,z)=[-\alpha_j+g_jP(t,z)]\,S_j(t,z)\quad j=1,\dots,N \\ \left(\frac{\partial}{\partial z}+\frac{1}{\upsilon}\frac{\partial}{\partial t}\right)P(t,z)=\left[\alpha_p+\sum_{j=1}^{N}\hat{g}_j S_j(t,z)\right]P(t,z) \end{cases} \quad (1)$$

where N is the number of WDM signals, α_p and α_j are the attenuations of pump and signals, g_j is the Raman gain coefficient $[W^{-1}m^{-1}]$ of the signal at wavelength λ_j, and $\hat{g}_j \triangleq g_j\lambda_j/\lambda_p$, being λ_p the pump wavelength. In this model we neglect spontaneous Raman scattering, Rayleigh backscattering, and direct signal to signal Raman crosstalk. We also assume that signals propagate at the same group velocity υ in the positive z direction, and that the pump propagates at the same velocity in the opposite direction. We now make the following time axis changes: $t_s \triangleq t - z/\upsilon$ and $t_p \triangleq t + z/\upsilon$, so as to recast the propagation equations in the signals and pump retarded time frames, and then explicitly solve such equations:

$$\begin{cases} S_j(t_s,z)=S_j^{in}(t_s)\exp\left\{-\alpha_j z+g_j\int_0^z P(t_s+dz')dz'\right\} \\ P(t_p,z)=P_0 e^{-\alpha_p(L-z)}e^{-\Gamma(t_p,z)} \end{cases} \quad (2)$$

where: $S_j^{in}(t_s)$ is the input signal power; $d \triangleq 2/\upsilon$ is the pump-signals walkoff parameter; P_0 is the launched pump power; L the amplifier length; and $\Gamma(t_p,z) \triangleq \sum_{j=1}^{N}\hat{g}_j\int_z^L S_j(t_p-dz')dz'$ characterizes the pump depletion caused by the signals. For moderate pump depletion we approximate $e^{-\Gamma} \cong 1-\Gamma$, and the signal power at the amplifier output can thus be written as:

$$S_j^{out}(t_s) \triangleq S_j(t_s,L) = S_j^{in}(t_s)\exp\{-\alpha_j L + Q_j(1-e^{-\alpha_p L})(1-x(t_s))\} \quad (3)$$

where $Q_j \triangleq g_jP_0/\alpha_p$,[6] and

$$x(t_s) \triangleq \frac{1}{L_{eff}^{(p)}}\int_0^L e^{-\alpha_p(L-z')}\Gamma(t_s+dz',z')dz' \quad (4)$$

being $L_{eff}^{(p)} \triangleq (1-e^{-\alpha_p L})/\alpha_p$ the effective length at λ_p. From (3), $x(t_s)$ can be interpreted as the *relative change in injected pump power sensed by the signals at retarded time* t_s. From (4), we find that the state variable $x(t_s)$ approximately satisfies the following implicit integral equation:

$$x(t_s)=\sum_{j=1}^{N} S_j^{out}(t_s,x(t_s))\otimes h_j(t_s) \quad (5)$$

where $S_j^{out}(t_s, x(t_s))$ is given in (3), the symbol $\otimes$ denotes convolution, and h_j is the impulse response of a linear filter:

$$h_j(t)=\frac{\hat{g}_j}{dL_{eff}^{(p)}G_j(L)}\left[\int_0^{L-\frac{t}{d}}e^{-\alpha_p(L-z')}G_j\left(z'+\frac{t}{d}\right)dz'\right]\cdot p(t) \quad (6)$$

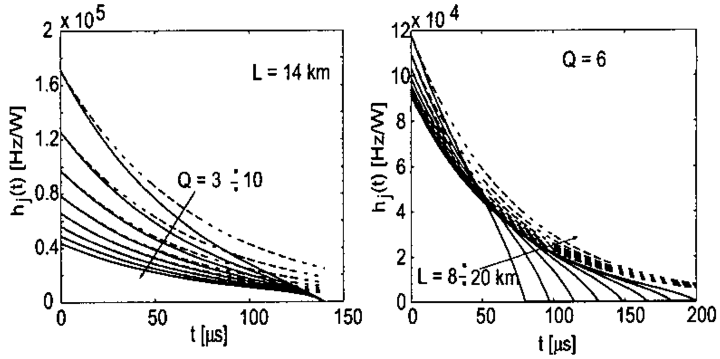
where $G_j(z) = \exp\{\alpha_j L + Q_j e^{-\alpha_p L}(e^{\alpha_p z}-1)\}$ is the gain-versus-z profile in the *undepleted pump* approximation,[6] and $p(t)$ is a gating function which equals 1 for $0 \le t \le dL$, and 0 elsewhere. For long amplifiers ($L >> 1/\alpha_p$) the filter can be simply approximated as a single pole lowpass: $h_j(t) \cong h_{j0}e - \frac{\alpha_p t}{d}$, where:

$$h_{j0}=\frac{\hat{g}_j}{d}e^{-Q_j}\sum_{n=0}^{\infty}\frac{Q_j^n}{(n+1-\frac{\alpha_j}{\alpha_p})\,n!} \cong \frac{\hat{g}_j}{dQ_j} \quad (7)$$

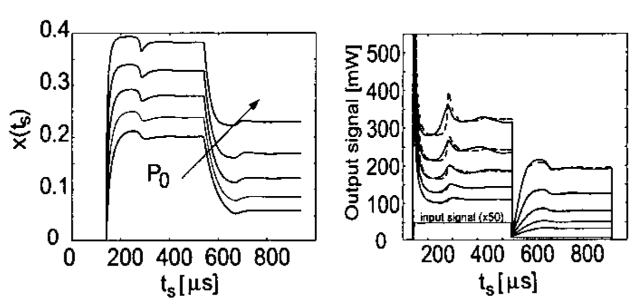
the last approximation being valid for large Q_j.

Fig. 1 shows $h_j(t)$, eq. (6), and its exponential approximation, for (left) a 14 km amplifier and increasing values of Q, and (right) for Q = 6 and increasing L. All filters are zero beyond $t = dL$, which is twice the propagation time inside the amplifier (we assumed $\upsilon = 2 \cdot 10^8$ m/s). In the calculations we used α_j = 0.46 dB/km, α_p = 0.6 dB/km, $g_j = 2 \cdot 10^{-3}$ [1/m/W], corresponding to a dispersion compensating fiber (DCF) with signal wavelength λ_j = 1545.3 nm, and pump wavelength λ_p = 1454.7 nm.[5]

We next solved the implicit equation (5) recursively, by performing the numerical convolution on the right hand side, and updating $x(t_s)$ as the average between its old value and its new value obtained from the convolution. Fig. 2 shows the relative pump change $x(t_s)$ (left) and the out-



ThR1 **Fig. 1.** Filter impulse response $h_j(t)$ (solid line) and its exponential approximation (dashed line).



ThR1 **Fig. 2.** (Left) relative pump change sensed by the signal, and (Right) output signal power, for increasing levels of pump power P_0 = 0.64, 0.70, 0.77, 0.86, 0.92 W. Solid lines: exact solution of (1); Dahed lines: model (5). Input signal shown (right) magnified 50 times.

put signal power $S_j^{out}(t_s)$ (right), calculated as in (5), (3) (dashed lines), and the exact numerical solution of the propagation equations (1) (solid lines) when the input signal is a single wavelength sequence of two contiguous packets of duration 400 µs each, the first with power 1 mW and the second 0.1 mW. Five different curves are reported in each subfigure, obtained for pump powers P_0 = 0.64, 0.70, 0.77, 0.86, 0.92 W, corresponding to saturated gains of 20 to 25 dB, respectively. We note that the approximate solution (5) very well reproduces the exact numerical solution as long as $x < 0.3$, the approximation becoming worse when the linearization $e^{-\Gamma} \cong 1$ fails. As seen in the figure, the power spike at the signal's leading edge can be several times the steady-state saturated value reached after the transient, and can be evaluated as $S_j(0)/S_j^{ss}=e^{Q_j(1-\exp\{-\alpha_p L\})x^{ss}}$, where ss denotes the steady state values.

The time constants involved in the transients can be easily made explicit when using the single-pole exponential approximation of the filter. In such case in fact equation (5) becomes an ordinary differential equation (ODE):

$$\dot{x}(t) = -\frac{x(t)}{\tau} + \sum_{j=1}^{N} h_{j0} S_j^{out}(t, x(t))$$

with $\tau \triangleq d/\alpha_p$ and h_{j0} as in (7). Such ODE is quite similar to the dynamical equation of the average inversion in doped fiber amplifiers.[3] With a linearization of the ODE as in,[4] we find that the response to N step input WDM signals has an approximate exponential behavior with time constant:

$$\tau_{eff} = \frac{d}{(\alpha_p + \sum_{j=1}^{N} \hat{g}_j S_j^{ss} G_j^{ss}(L))}$$

where S_j^{ss} is the steady-state input power of the j-th signal before the step discontinuity, and $G_j^{ss}L)$ is its saturated steady-state gain before the step. Thus, power transients in saturated Raman amplifiers can be much faster than the time constant d/α_p characterizing pump-induced relative intensity noise,[7] depending on the total saturating power $\sum_{j=1}^{N} S_j^{ss} G_j^{ss}(L)$, a behavior very similar to that of saturated EDFAs.[4] However, due to the large propagation delay inside Raman amplifiers, standard gain clamping techniques known for EDFAs cannot be applied to mitigate the gain fluctuations. A simple countermeasure is the adoption of a hybrid dual-stage Raman-EDFA configuration, in which the first Raman stage does not reach output signal powers large enough to deeply saturate it, and the following EDFA stage can then be gain clamped.

References

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ThR2 **2:15 pm**

Transient gain dynamics in wide bandwidth discrete Raman amplifiers

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Introduction

Discrete Raman amplifiers are an attractive solution for providing wide bandwidth and low noise amplification in fiber-optic telecommunication systems.[1] Wide bandwidth WDM Raman amplifiers employing multiple pump wavelengths are very complicated systems due to the number of pump-to-pump, pump-to-signal and signal-to-signal Raman interactions which take place. Any change in the input conditions to such an amplifier will modify all of these interactions and can potentially cause significant channel power transients, particularly if the amplifier is operating in a saturated regime. Previous measurements of transient effects in Raman amplifiers have been performed on amplifiers having only a single pump wavelength and single signal wavelength.[2]

In this paper I present a detailed experimental study of the transient gain dynamics caused by adding or dropping channels at the input of a backward pumped 60 nm bandwidth WDM discrete Raman amplifier employing multiple pump wavelengths. Monitoring edge signal channels and all pump wavelengths provides a better understanding of the complex power transfer changes that occur with changes in signal loading.

Experiment

The configuration of the Raman amplifier used in these measurements is shown in figure 1. The gain medium is 3 km of a low loss Ge-doped step index fiber with a refractive index delta of 3%. The attenuation of the fiber is 0.87 dB/km at 1550 nm and 1.08 dB/km at 1480 nm. The maximum Raman gain coefficient for 1480 nm pumping is 5.5 W^{-1} km^{-1}.

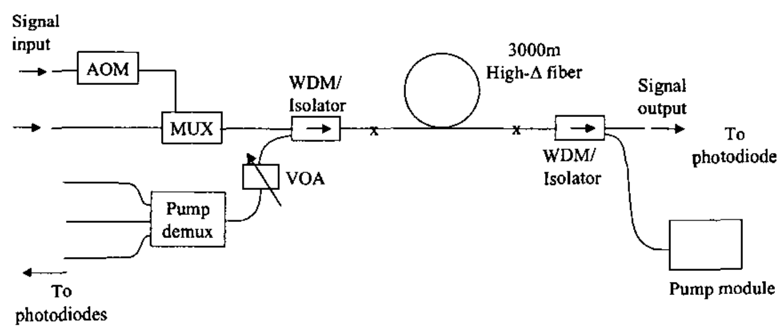
The amplifier is backward pumped at wavelengths of 1460, 1480 and 1510 nm. Each pump wavelength is generated using a pair of polarization multiplexed fiber Bragg grating stabilized laser diodes. The unabsorbed pump light is coupled out of the amplifier and demultiplexed to allow measurements of the pump power remaining at each pump wavelength. A VOA is included to reduce the power of the unabsorbed pump light to a level at which it can be monitored on a photodiode.

The input to the amplifier was 44 WDM channels on the ITU grid between 1563 and 1621 nm with a power of −10 dBm/channel. Thirteen wavelength channels between 1587 and 1602 nm were passed through an acousto-optic modulator (AOM), before being combined with the remaining channels, to allow adding or dropping of these channels at the input.

Initially, the gain and noise figure of the amplifier was measured in the steady state with all of the channels present and the pumps adjusted to give a minimum gain of 12 dB with a ripple of 1 dB. This required pump a total pump power of 875 mW at the output of the pump module (385 mW at 1460 nm, 268 mW at 1480 nm and 222 mW at 1510 nm). This gave a total signal output power of 80 mW. The unabsorbed pump power was 30 mW at 1460, 56 mW at 1480 and 200 mW at 1510 nm.

The noise figure varied from 4.8 dB at 1621 nm to 5.6 dB at 1563 nm and includes the loss of the input isolator and WDM. Wavelengths 1587–1602 nm were then dropped from the input by switching off the AOM and the new steady state gain and noise figure were measured without adjusting the pump powers. These measurements are shown in figure 2. After dropping the center channels, the gain of the surviving channels increases by approximately 0.5 dB across the whole wavelength range. The noise figure of the surviving channels is unaffected. After dropping the center channels, the total output power in the surviving channels was 65 mW and the unabsorbed pump powers changed to 29 mW at 1460 nm, 57 mW at 1457 nm and 214 mW at 1510 nm.

The time dependent behavior of the surviving channels was then measured in response to the center wavelength channels being dropped by the AOM. This was measured by selecting one of the surviving channels with a Fabry-Perot filter



ThR2 Fig. 1. Amplifier configuration.