Transient Gain Dynamics in Saturated Counter-pumped Raman Amplifiers

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Outline

- ✔ Motivation
- ✔ New State-Variable Model
- ✔ Results
- ✔ Conclusions

Motivation

- Saturation-induced gain transients (Cross-gain modulation):

  Chen and Wong, OAA 2001, paper OMC2

- Physical reason: pump-signal walkoff

  signal front grows and depletes pump

  ⇨ signal body finds less pump than front

- Need to Quantify:

  Power surges, time constants of transients

☞ Need a system model !

Propagation Equations

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

where: S_j signal [W]; υ speed [m/s]; g_j Raman gain [1/W/m]; α attenuation [1/m]; P pump [W]; $\hat{g}_j \triangleq g_j \lambda_j / \lambda_p$

Neglect:

- ✘ ASRS noise
- ✘ Rayleigh Backscattering
- ✘ direct signal-signal crosstalk

Implicit Solution

Solution of propagation equations in the signals and pump *retarded time frames* $t_s = t - z/\upsilon$, $t_p = t + z/\upsilon$ is

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

where: $S_j^{in}(t_s)$ input signal [W]; $d \triangleq 2/\upsilon$ [s/m] walkoff parameter; P_0 launched pump [W]; L amplifier length [m]; and

$$\Gamma(t_p,z) \triangleq \sum_{j=1}^{N} \hat{g}_j \int_z^L S_j(t_p - d\,z', z')dz'$$

is the *pump depletion in the pump time frame*.

The State Variable

At moderate pump depletion $e^{-\Gamma} \cong 1-\Gamma$. Signal power at output is thus

$$S_j^{out}(t_s) = S_j^{in}(t_s)\exp\left\{-\alpha_j L + Q_j(1-x(t_s))\left(1-\mathrm{e}^{-\alpha_p L}\right)\right\}$$

where $Q_j \triangleq \frac{g_j}{\alpha_p} P_0$ and

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

is the *relative change in injected pump power sensed by the signals at retarded time* t_s.

☞ Once $x(t_s)$ is known, all WDM output signals are known !

The State Equation

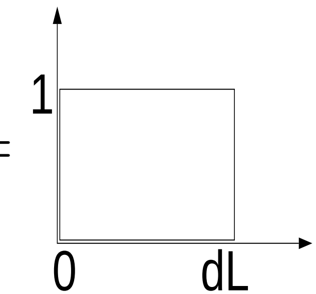
The state variable $x(t_s)$ satisfies the following implicit integral equation

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

where $\otimes$ denotes convolution, and h_j is the impulse response of a linear filter:

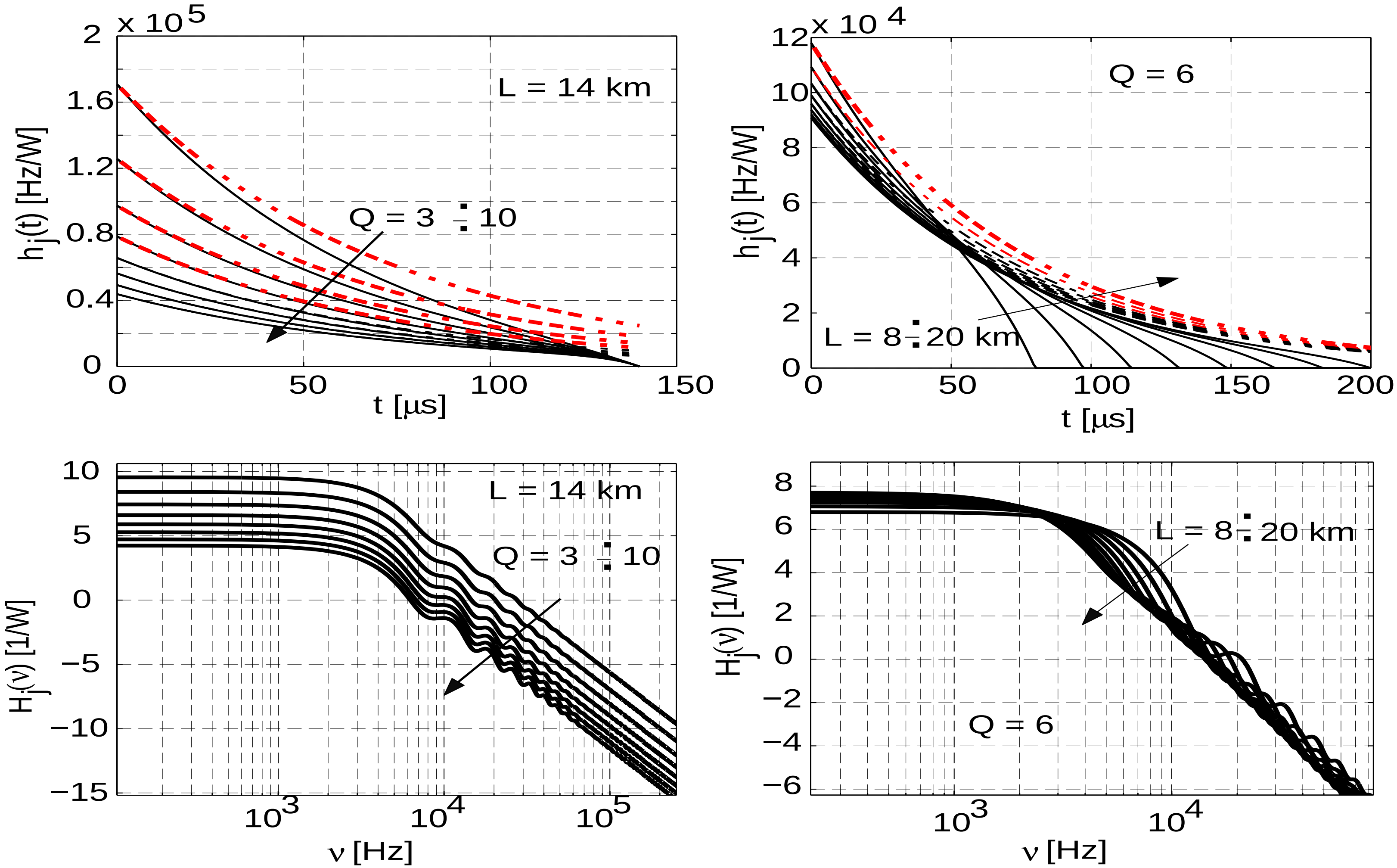
$$h_j(t) = \frac{\hat{g}_j}{d\,L_{eff}^{(p)} G_j(L)} \left[\int_0^{L-\frac{t}{d}} \mathrm{e}^{-\alpha_p (L-z')} G_j\left(z' + \frac{t}{d}\right) dz'\right] \cdot p(t)$$

where $G_j(z)$ is the *unsaturated* gain-versus-z profile, and $p(t) =$



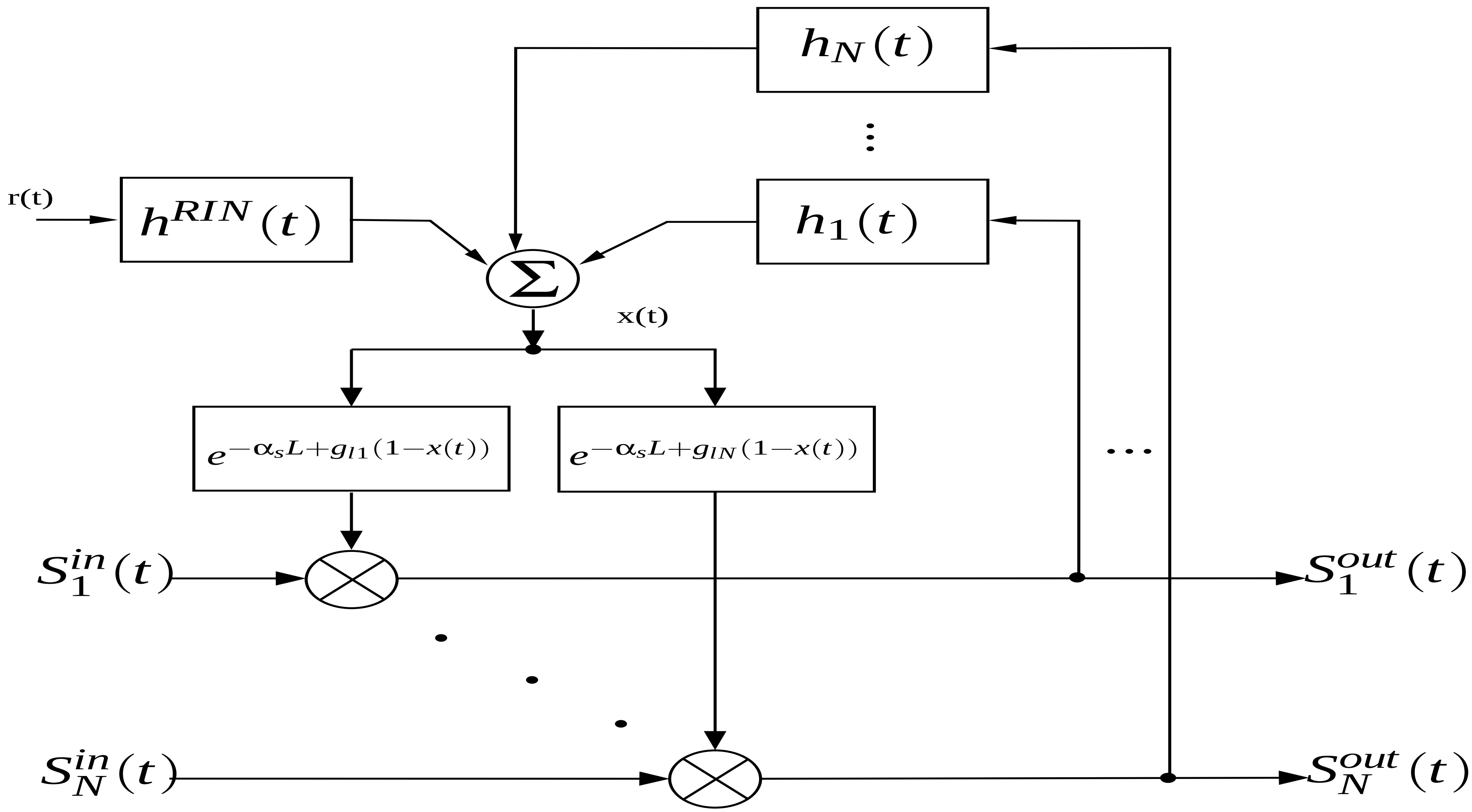
Filter

A **closed-form** of such filter exists. For a DCF with $\alpha_j = 0.46$ dB/km, $\alpha_p = 0.6$ dB/km, $g_j = 2$ [$W^{-1}km^{-1}$] get: (- - exponential approx.)



Amplifier Block Diagram

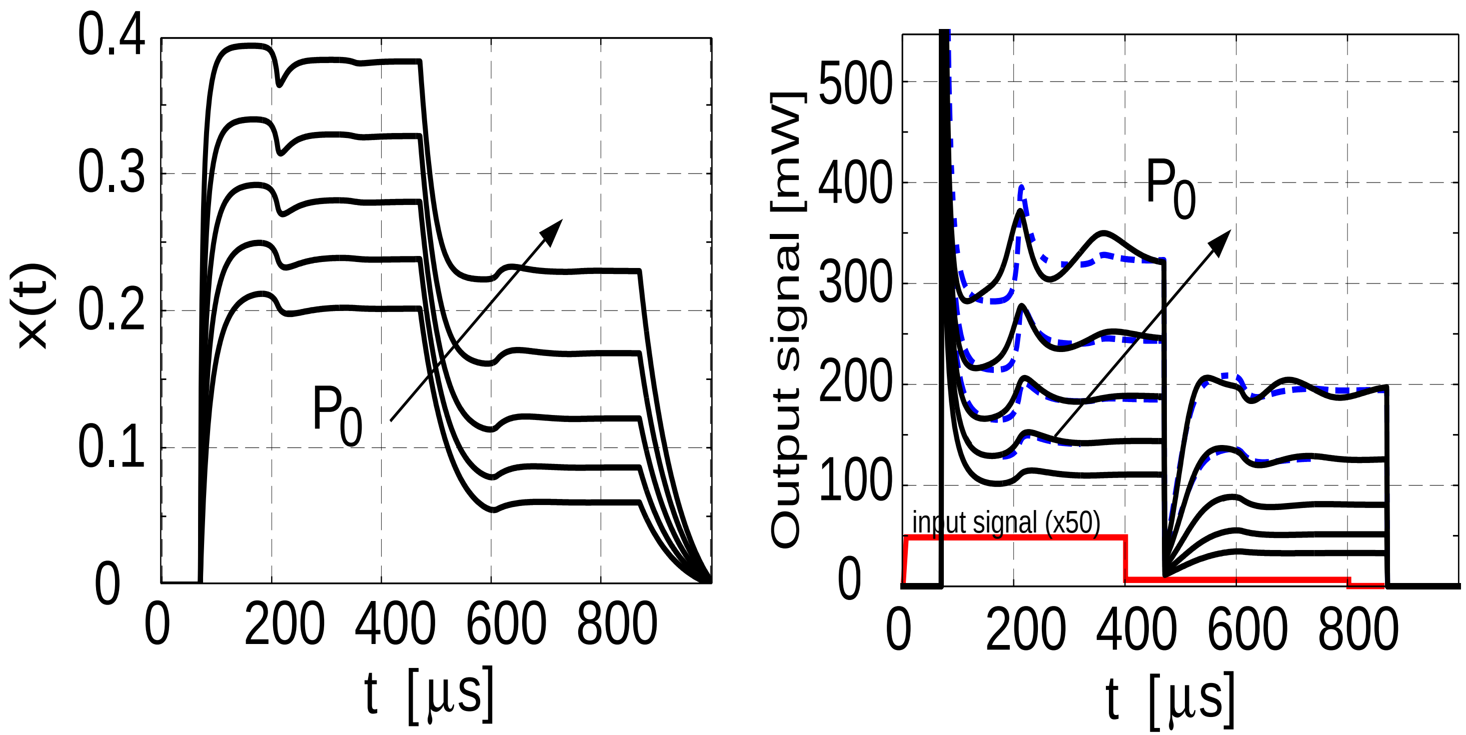
RIN filter: Cfr Fludger *et al*, JLT Aug '01.



Can be implemented in any Block-Diagram Simulator!

Results: Single Channel

Two Pulses of 1 and 0.1 mW, 400 μs each. Ampli: L=14 km, DCF.

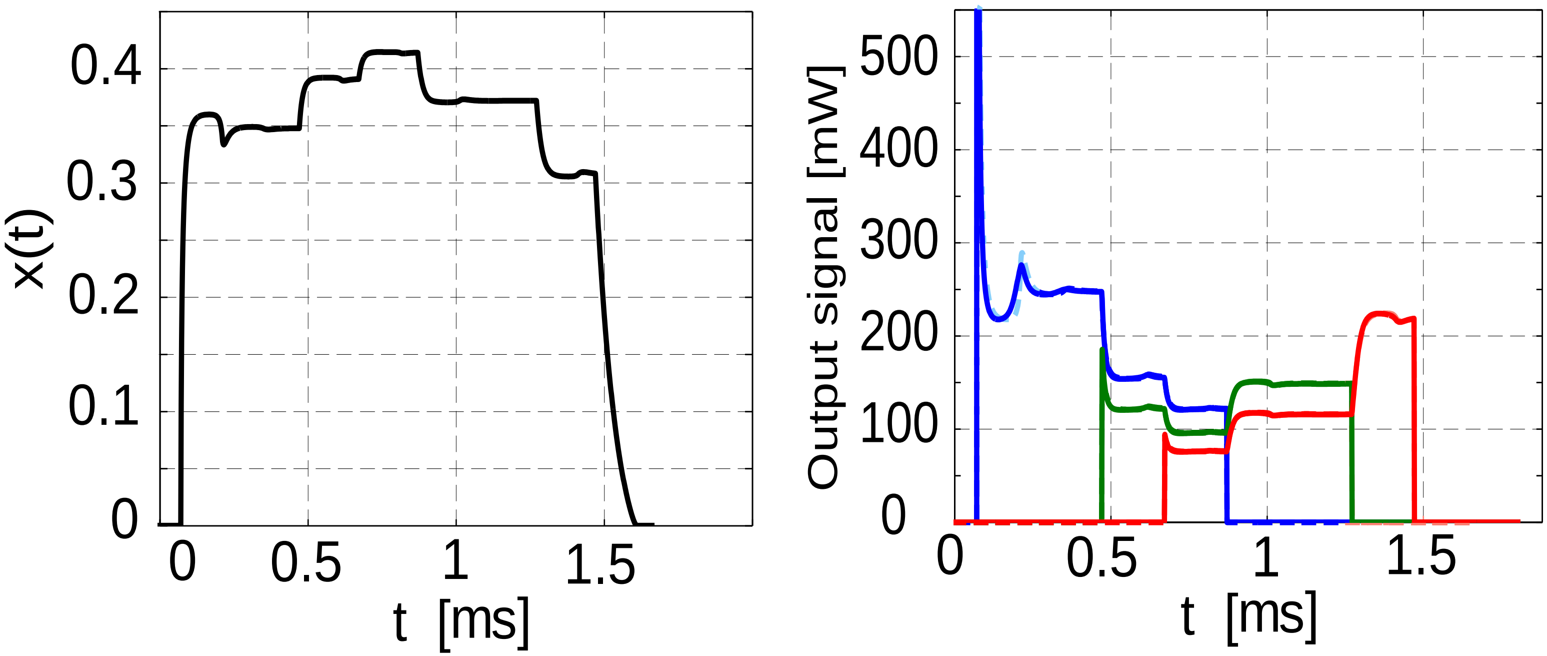


(Left) state variable, and (Right) output signal power, for increasing levels of pump power $P_0 = 0.64, 0.70, 0.77, 0.86, 0.97$ W. Solid lines: exact solution (+DRB); Dahed lines: model.

Results: WDM

Three staggered pulses (1 mW, 800 μs each) on 3 channels, $\Delta\lambda = 0.4$ nm.

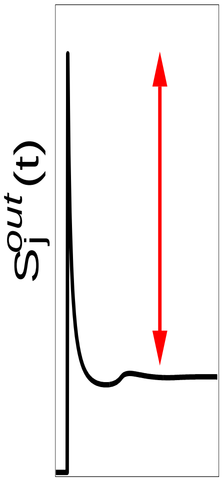
L=14 km, DCF.



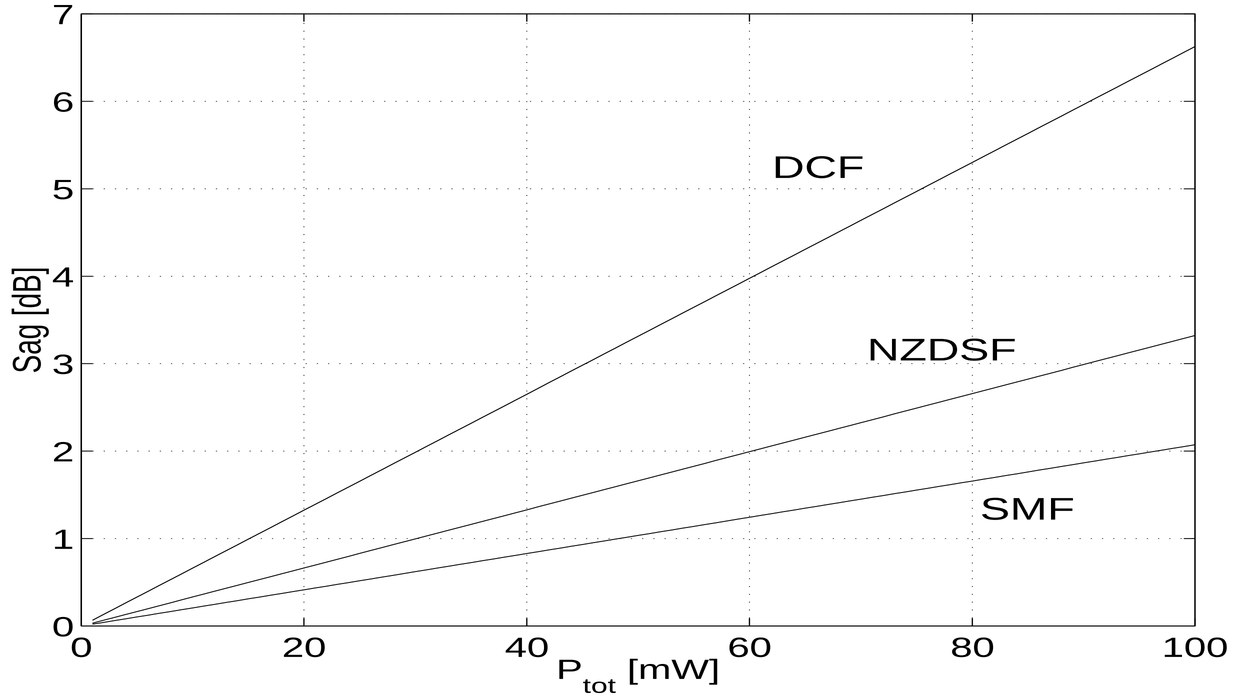
(Left) state variable, and (Right) output signal powers, for pump power $P_0 = 0.86$ W. Solid lines: exact solution (+SS xtalk, +DRB); Dahed lines: model.

Power surges

The power Sag across a pulse is:



$$\left.\frac{S_j^{out}(0)}{S_j^{out}(x^{ss})}\right|_{dB} \cong (10\log_{10}\mathrm{e})\left[\frac{\hat{g}_s}{\alpha_p}\underbrace{\left(\sum_{i=1}^{N} S_i^{out}(x^{ss})\right)}_{\text{Ptot}}\right]$$



Time constants

Using exponential approximation $h_j(t) \cong h_{j0} e^{-\frac{\alpha_p}{d} t}$, state equation becomes an ordinary differential equation (ODE), similar to that for EDFAs:

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

with $\tau \triangleq d/\alpha_p$ playing the role of the fluorescence time.

Using standard linearization technique (Y. Sun *et al.*, JLT, July 97) we find:

$$\tau_{eff} \cong \frac{d/\alpha_p}{1 + \left[\frac{\hat{g}}{\alpha_p}\left(\sum_{i=1}^{N} S_i^{out}(x^{ss})\right)\right]}$$

Conclusions

- XGM present also in Raman amplifiers
- New state-variable model of counter-pumped saturated Raman amplifiers
- Closed-form expressions for power surges and time constants of transients