Dynamic Behavior in Raman Fiber Amplifiers

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Abstract - **In this paper the comparison of the transient responses of the surviving channels in a C-band dispersion-shifted fiber (DSF) and dispersion-compensating fiber (DCF) based Raman fiber amplifiers (RFA) are presented. Counter-pumped and co-pumped configurations are analyzed.**

Index Terms – **Raman fiber amplifier, Power transient, Optical communications.**

I. Introduction

RFAs are being used in optical communication systems in the recent years due to their advantages in comparison to EDFAs: the Raman gain exists in every fiber; the gain is available over the entire transparency region of the fiber; the gain spectrum of Raman amplifiers may be tailored by adjusting the pump wavelength configuration, improved noise figure and reduced nonlinear penalty [1].

Much work have been done to design and analyze RFAs, and as in the EDFAs the analysis of dynamic behavior of these amplifiers has become important to predict the system response to add/drop of channels or cable cuts in optical systems, which could help the implementation of control systems to avoid the power transients in dynamic systems [2][4].

The aim of this paper is to compare numerically the signal power transients in the surviving channels in DCF and DSF based RFAs. In the second section of this paper, the numerical model used to simulate the transient effects in RFAs is introduced and the simulation setup is explained. Finally, in the third section the results of the simulations are presented. Counter-pumped and co-pumped pump RFA configurations are considered.

II. Numerical Modeling and Simulations

The numerical model used to describe the dynamic behavior of a RFA is based on the one derived in [3]. The physical effects taken into account in this model are:

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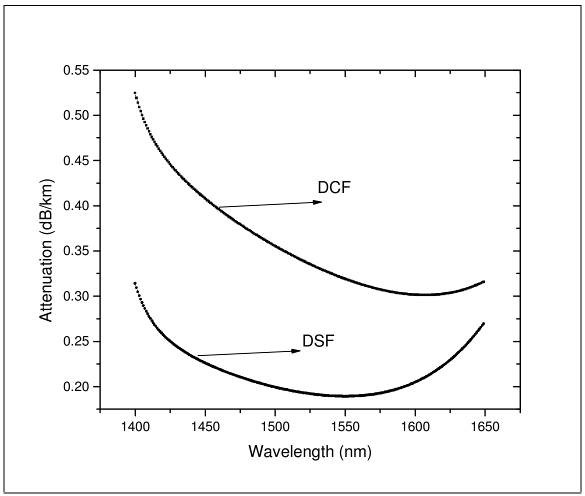
Pump-to-pump, signal-to-signal and pump-to-signal Raman interactions; spontaneous Raman emission and its temperature dependency; stimulated Raman scattering; pump depletions due to Raman energy transfer; high-order stokes generation; multiple Rayleigh backscattering; fiber loss dependent on the wavelength; and spontaneous emission noise. When all these effects are considered, the propagation equations describing the forward and backward powers evolution are written in the following form:

$$\begin{aligned}
&\frac{\partial P^{\pm}(z,t,\upsilon)}{\partial z} \mp \frac{1}{V_g(\upsilon)}\frac{\partial P^{\pm}(z,t,\upsilon)}{\partial t} = \mp\alpha(\upsilon)P^{\pm}(z,t,\upsilon) \pm \gamma(\upsilon)P^{\mp}(z,t,\upsilon) \pm \\
&P^{\pm}(z,t,\upsilon)\sum_{\nu<\varsigma}\frac{g_r(\upsilon-\varsigma)}{K_{eff}A_{eff}}\left[P^{\pm}(z,t,\varsigma)+P^{\mp}(z,t,\varsigma)\right] \pm \\
&h\Delta\upsilon\sum_{\upsilon<\varsigma}\frac{g_r(\upsilon-\varsigma)}{A_{eff}}\left[P^{\pm}(z,t,\varsigma)+P^{\mp}(z,t,\varsigma)\right]\cdot\left[1+\left(\exp\left[\frac{h(\varsigma-\upsilon)}{kT}\right]-1\right)^{-1}\right] \mp \\
&P^{\pm}(z,t,\upsilon)\sum_{\upsilon>\varsigma}\frac{g_r(\upsilon-\varsigma)}{K_{eff}A_{eff}}\frac{\upsilon}{\varsigma}\left[P^{\pm}(z,t,\varsigma)+P^{\mp}(z,t,\varsigma)\right] \mp \\
&2h\upsilon\Delta\upsilon P^{\pm}(z,t,\upsilon)\sum_{\upsilon>\varsigma}\frac{g_r(\upsilon-\varsigma)}{A_{eff}}\left[1+\left(\exp\left[\frac{h(\upsilon-\varsigma)}{kT}\right]-1\right)^{-1}\right]
\end{aligned} \tag{1}$$

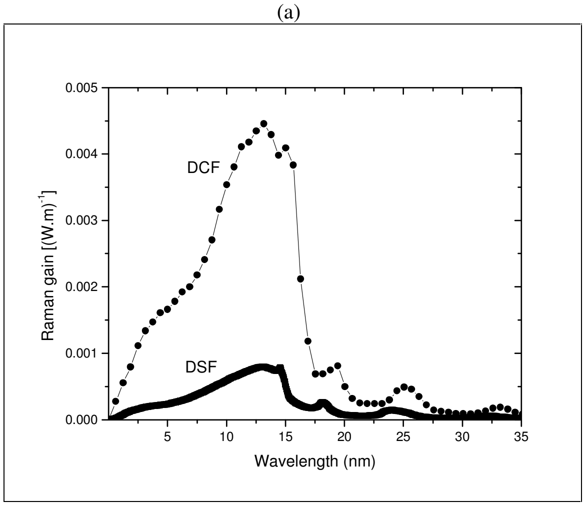
Where υ,ζ are the wave frequencies [Hz], $P^{+}(z,t,\upsilon)$ is the forward power of signal (pump) at frequency υ [W], $P^{-}(z,t,\upsilon)$ is the backward power of signal (pump) at frequency υ [W], $V_g(\upsilon)$ is the frequency-dependent group velocity, $\alpha(\upsilon)$ is the fiber attenuation [N/m], $\gamma(\nu)$ is the Rayleigh backscattering coefficient [N/m], $g_r(\nu-\zeta)$ is the Raman gain coefficient for frequency difference $(\upsilon-\zeta)$ [m/W], A_{eff} is effective area [m^2], K_{eff} is polarization factor, $\Delta\upsilon$ is the frequency interval [Hz], h is the Plank's constant, k is the Boltzman's constant, and T the absolute temperature of the fiber [K].

For the solution of (1), first of all, the steady-state solution is found through the application of the fourth-order Runge-Kutta. This first result comprehends the longitudinal distribution of all individual powers (pumps, signals, ASE waves) along the fiber. Then, this solution is directly integrated [5] and the time evolution of pumps, signals and ASE waves is acquired. In order to guarantee that the solution in time domain does not present undesirable oscillations, we must take care to choose wisely the bin widths in space (Δz) and time (Δt). The stable solution has just been obtained [1] when the time bin Δt is equal or smaller than the propagation time through the space bin, i.e., $\Delta t \leq \Delta z / V_g$. This numerical model was implemented in a commercially available simulation tool used for the simulations♦.

The Raman gain efficiency, that is defined as the ratio g_r / A_{eff} , and the fiber loss characteristics of the DSF and DCF fibers used in the simulations are displayed in Figure 1. The advantage in using the Raman gain efficiency instead of the Raman gain coefficient and the effective area separately lies on the fact that we need to measure just one characteristic of the fiber [6].



(a)

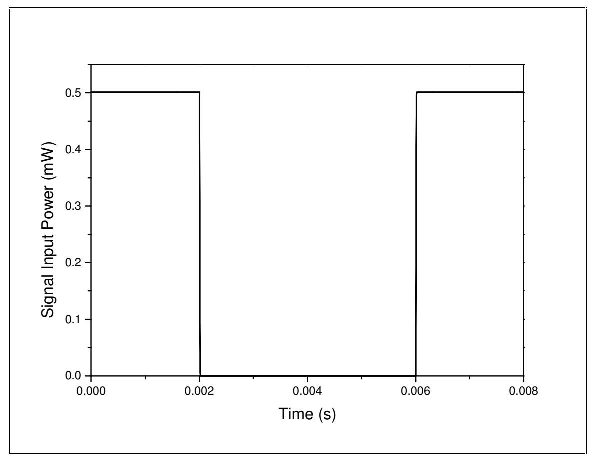


(b)

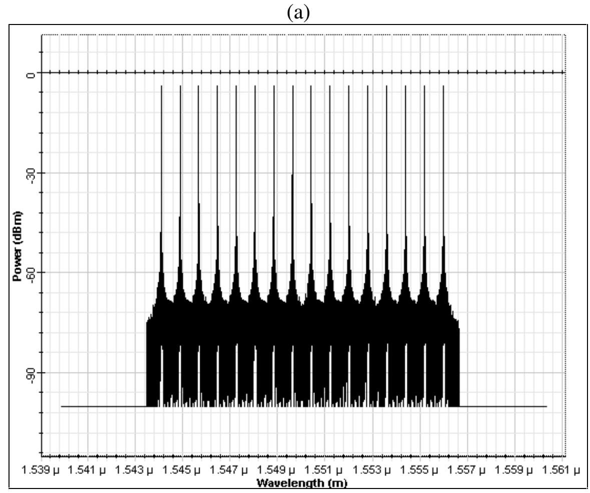
Figure 1 – (a) Attenuation and (b) Raman gain efficiency for the two fibers used in the simulations.

The fiber length for each RFA is 50 km for the DSF and 10 km for the DCF (These parameters are close to those of [2,3]). The pump in both RFAs was fixed at 1450nm and its power was 800 mW and 200mW for the DSF and DCF, respectively, for the counter and co-pumped cases.

The system simulated has 16 channels occupying a bandwidth of 12nm ranging from 1544 nm to 1556 nm and channel spacing equals to 0.8nm, see Figure 2(b). Each input signal launches -3dBm optical power into the fiber, what leads the amplifier to operate in a saturation regime. Some of these channels are 100% square wave modulated with frequency f_m= 125Hz and 50% duty-cycle to simulate the add/drop of channels. Three different partners were considered here. In the first one, we dropped and then added 2 signals (1544nm and 1556 nm). In the second one, the procedure is repeated with 4 signals (1544 nm, 1544.8 nm, 1555.2 nm and 1556 nm). Finally, in the third one 8 signals (1544 nm, 1544.8 nm, 1545.6 nm, 1546.4 nm, 1553.6, 1554.4, 1555.2 nm and 1556 nm) are added/dropped. The signals are always dropped at 2ms and added at 6 ms. Figure 2(a) shows the input modulated signal of the channel at 1544 nm.



(a)



(b)

Figure 2 – (a) Modulated signal at 1544 nm to represent the add-drop of channels. (b) Channels distribution.

♦ OptiSystem 3.0, Optiwave Corporation

III. RESULTS AND DISCUSSION

Figure 3 shows the output signal powers, considering a CW case, for the 16 channels launched in both RFAs for the two pump schemes. These results are used as reference for the calculation of the power excursion of each channel.

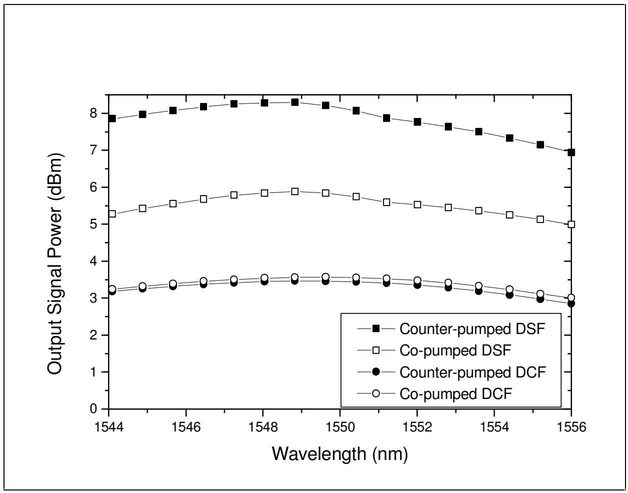


Figure 3 – RFA output signal powers for DCF and DSF fiber.

The results presented in the next sections are the transient power excursions of the surviving channel at 1550.4 nm caused by the add-drop of signals.

A. DCF Case

Figure 4 shows the power excursions on a surviving channel for the RFA counter-pumped.

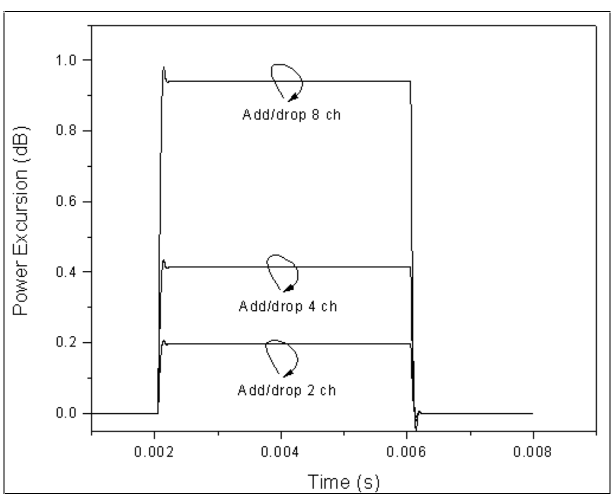


Figure 4 – Output-surviving signal at 1550.4 nm for a DCF counter-pumped.

The leading-edge (drop of channels) in the output signal overshoots and then reaches a new steady-state condition. In the trailing-edge (add of channels) of the output signal appears an undershoot and then the signal reaches the steady-state condition again. The transients in leading-edge are caused by the lower saturated gain that the surviving channels experience when some channels are dropped. The stronger power in the front signal leads to the depletion of the pump, and the remaining signal does not experience the same gain as in the leading edge due the lower pump power. In the case of the trailing-edge, after the addition of the channels, the pump is more depleted and because it propagates backward the fiber, the signal get a lower gain than the steady-state saturated gain.

Unlike of the counter-pumped RFA, in the co-pumped configuration the overshoot and undershoot were not noticed, as showed in Figure 5. Even when the number of add/drop channels was increased, the presence of them was not clearly noticed.

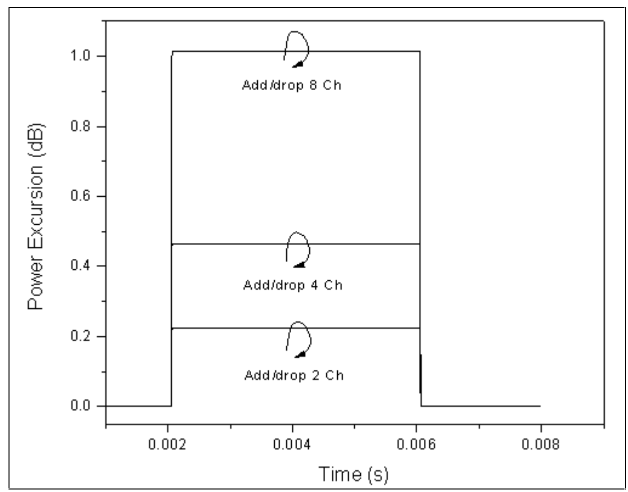


Figure 5 – Output-surviving signal at 1550.4 nm for a DCF co-pumped.

The transients occur faster in the co-pumped RFA due to the fact that the pump and surviving signals are propagating in the same direction with approximately the same group-velocities.

Can be noticed that the power excursion is larger in the counter-pumped case. It happens because in the counter-pumped scheme the amplifier is more saturated.

B. DSF Case

Figure 6 shows the power excursions on surviving channels for the RFA counter-pumped.

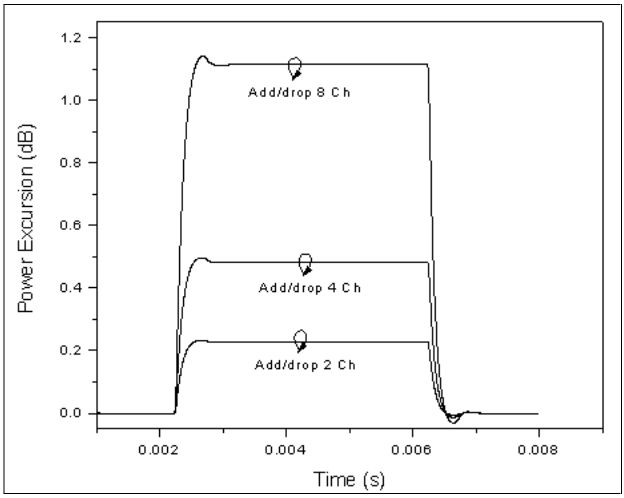


Figure 6 – Output-surviving signal at 1550.4 nm for a DSF counter-pumped.

The curves show the overshoot and undershoot like in the DCF counter-pumped, however, in the DSF case the transients are longer, which could be explained by larger length of fiber [3].

In the co-pumped RFA, Figure 7, the transient effects presents a behavior similar to that found in the co-pumped DCF case; the transients are very fast and the steady-state condition is soon reached.

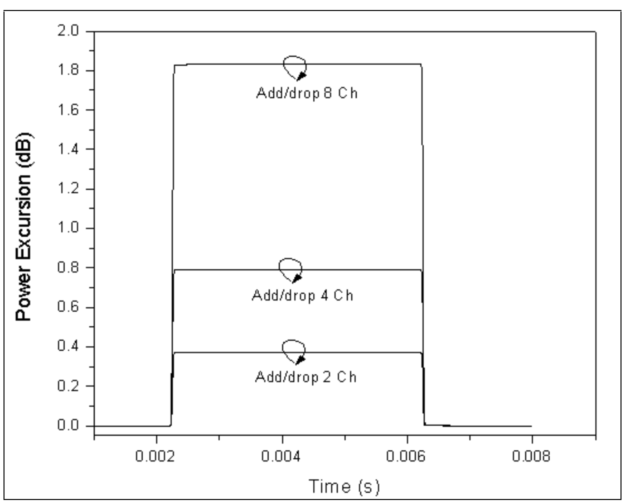


Figure 7 – Output-surviving signal at 1550.4 nm for a DCF co-pumped.

IV. CONCLUSION

The transient's effects in Raman fiber amplifiers have been demonstrated using two different fibers. The RFA presents transients effects that could cause problems in the optical systems.

In the case of counter-pumped RFA, the problems caused by overshoots can be even worst when a cascade of RFAs is considered.

For co-pumped RFAs, their fast transients can create difficulties to project an effective gain/power control system to handle dynamic optical systems.

Further studies are being pursued to analyze the transient's effects in cascades of RFAs and in hybrids amplifiers.

V. REFERENCES

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