Analysis of a Pump Reflecting Raman Fiber Amplifier

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***Abstract*—We analyze the pump reflecting Raman fiber amplifier in the steady-state and in the dynamic regime. The numerical model is based on the propagation equations of the Raman fiber amplifier (RFA), which incorporates time and space variation. An experimental validation of the model is made. To better understand the impact of reflecting the pump power back into the amplifier fiber, a comparison with the traditional pumping scheme is presented. Results show that the reflection of the pump power increases the amplifier efficiency, but it also increases the transient response in the surviving channel.**

***Index Terms*—Optical communication, Raman fiber amplifiers, Transient effect.**

I. INTRODUCTION

When the objective is the development of low cost Raman fiber amplifiers (RFA), the efficiency of the amplifier is an important aspect. Knowing that the RFA does not use all the input pump power, several solutions have been proposed to increase the efficiency of the RFA. One of them, is based on the inclusion of a fiber Bragg grating (FBG), centered in the pump wavelength, to reflect the unused pump power back into the amplifier [1]. In Fig. 1 the scheme of the amplifier configuration is presented. With this configuration, the FBG act as a second pump, re-injecting the unused pump power back into the amplifier fiber, increasing the amplifier efficiency.

With the implementation of the dynamic optical networks, channels add/drop are going to occur due to the network reconfiguration. These channels add/drop leads to output power fluctuations in the surviving channels, called transient effects [2]. These transient effects can degrade the signal quality in WDM optical networks [3]. Therefore, to understand if this amplifier configuration is suitable for developing a low cost Raman fiber amplifier, with the transmission fiber as the amplifier medium, it is important to analyze the amplifier behavior, when channels are added/dropped.

In this work we analyze the pump reflecting RFA behavior in the steady-sate and in the dynamic regime, with the purpose of understanding the advantages/disadvantages of this amplifier configuration. The numerical model implemented is based on the propagation equations [4] and the Average Power Analysis (APA) method [5]. An experimental validation of the model is made for the steady-state and for the dynamic regime.

This work is partially supported by the Consortium Telesal through the "DROM - Dimensionamento de Redes Ópticas Multicamada" project and through the "CRT - Controlo do Regime Transiente em Amplificadores Ópticos de Raman" project.

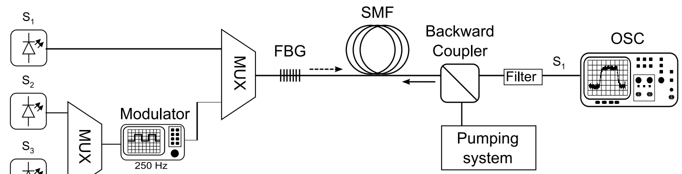

Fig. 1: counter-pumped RFA with a FBG to reflect the unused the pump power

In section II, the mathematical model used is presented. An experimental validation of the numerical model for the steady-state and for the dynamic regime is presented in section III. In section IV, an analysis of the counter-pumped RFA with a FBG is performed for the steady-state and for the dynamic regime. A comparison between traditional pumping schemes and this technique is also discussed in this section. The conclusions are presented in section V.

II. MATHEMATICAL MODEL

Simulations of the dynamic behavior of the RFA were performed by numerically solving the propagation equations of the Raman Amplifiers [3]. To reduce the simulation time, we neglect all the phenomena that contribute to the creation and the amplification of noise. Therefore the propagation equations can be expressed by:

$$\begin{aligned}\frac{\partial P_k^{\pm}(z,t)}{\partial z} \mp \frac{1}{v_{g,k}}\frac{\partial P_k^{\pm}(z,t)}{\partial t} &= \mp\alpha_k P_k^{\pm}(z,t)\\ \pm \sum_{j\neq k, j=1}^{N} g_{kj}[P_j^{\pm}(z,t) + P_j^{\mp}(z,t)]P_k^{\pm}(z,t),\end{aligned} \tag{1}$$

where z is the fiber length, t is the time, jth and kth identify the signals, $P_k^{\pm}(z,t)$ represent the optical power of the signal k propagating in the forward direction, $P_k^{+}(z,t)$, or in the backward direction, $P_k^{-}(z,t)$, α_k is the fiber loss coefficient for the signal k, N is the total number of interacting signals in the fiber, $v_{g,k}$ is the group velocity for the signal k, and g_{kj} is related with the Raman gain coefficient, $g_R(\nu)$, by:

$$g_{kj} = \begin{cases} \dfrac{g_R(\nu_j-\nu_k)}{2\,A_{eff}} & \text{if } \ \nu_j-\nu_k \geq 0 \\ -\dfrac{\nu_k}{\nu_j}\dfrac{g_R(\nu_k-\nu_j)}{2\,A_{eff}} & \text{if } \ \nu_j-\nu_k < 0, \end{cases} \tag{2}$$

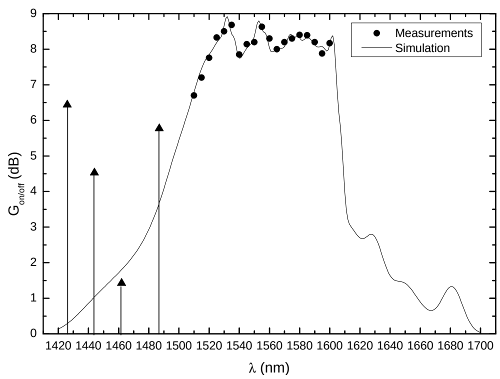

Fig. 2: On/Off gain for a Raman amplified system using four pumps in an 80 km SMF. The symbols represent the measurements and the line represents the simulation result

where A_{eff} is the fiber effective area, and ν_j and ν_k are the frequencies of the signal j and k, respectively. The Raman gain coefficient $g_R(\nu)$ of the SMF, is obtained using the technique presented in [6].

In the case of reflecting the pump power, we introduce a FBG in the opposite side of the pump, with the reflectivity of approximately 100% in the pump wavelength. The boundary condition are the following, for the backward pump:

$$\begin{aligned} P^-_{pump}(L,t,\nu) &= P_{pump}(\nu) \\ P^+_{pump}(0,t,\nu) &= P^-_{pump}(0,t,\nu) \end{aligned} \tag{3}$$

where $P_{pump,i}$ is the pump power injected in the fiber and $P^+_{refle,i}$ is the pump power reflected for the pump i, at the beginning of the fiber, $z = 0$.

III. Experimental validation

To validate the model we performe several experiments using multiple pumps. The main idea is to prove that the model can accuracy describe the behavior of the Raman amplifier using more than one pump.

A. Steady-state

In order to confirm the accuracy of the model described previously, we used four pumps in backward configuration, a tunable laser in continuous mode as the signal to be amplified and a Single Mode Fiber (SMF), with 80 km and an attenuation of 0.2 dB/km around 1550 nm, as the transmission path.

In this experiment we used four pumps centered at 1426 nm, 1444 nm, 1462 nm and 1487 nm with 175.4 mW, 113 mW, 55.3 mW and 150.3 mW, respectively. We measured the On/Off gain using the tunable laser as the signal. The signal power was fixed at 1 mW for all the signal wavelengths. We measured the signal power at the end of the amplifier with pumps on and with pumps off to obtain the On/Off gain. The results are presented in Fig. 2. As we can see, the experimental results are in agreement with the model results.

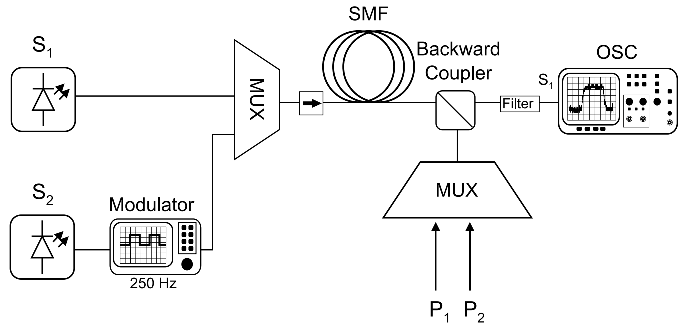

Fig. 3: Experimental setup used to measure the transiente effect of a counter-pumped RFA

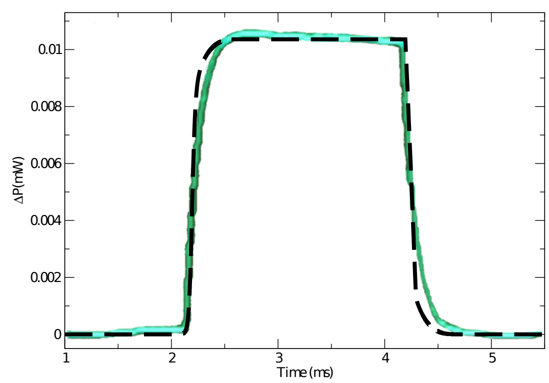

Fig. 4: Power fluctuation of the 1555 nm channel, as function of time, experimental and simulation (dashed line) results, when one channel is add/drop; L_{SMF} = 40 km; λ_p = 1427.5 nm, 1509 nm; $P^-_{p,in}$ = 98 mW and 144 mW, respectively; λ_s = 1555 nm, 1602 nm; $P_{s,in}$ = 3 mW, and 6 mW, respectively

B. Dynamic Regime

The experimental setup is presented in Fig. 3. We considered two pumps centered at 1427.5 nm and 1509 nm, with an input power of 98 mW and 144 mW. The fiber used is a single mode fiber with 40 km of length. The signal S_1 is centered at 1555 nm, and is continuous in time, with 3 mW of optical power. The signal S_2 is centered at 1602 nm with 6 mW of optical power. This signal is square-wave modulated with a frequency of 250 Hz with 50 % of duty cycle to reproduce the channel add/drop. An optical filter is used to select the surviving channel wavelength, in this case, 1555 nm. A digital oscilloscope is used to detect the time evolution of the surviving channel.

In Fig. 4 the experimental and the simulation results of the power fluctuations at the end of the amplifier, for the 1555 nm channel, are presented. The removal of the 1602 nm channel occurs at 2 ms, which leads to a power rise in the continuous signal. We also observe before the power start to increase, approximately 193 μs of the time delay, due to the channel propagation in the fiber. After the rise time a new steady-state is obtained with only one signal, S_1, in the

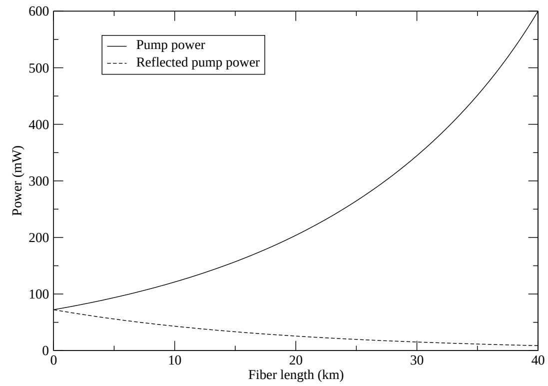

Fig. 5: Power distribution of the pump along the amplifier fiber, in a counter-pumped Raman fiber amplifier with a FBG; L_{SMF} = 40 km; λ_p = 1450 nm; $P_{p,in}$= 600 mW; λ_s = 1550 nm, 1551 nm, 1552 nm; $S_{p,in}$= 1 mW/channel

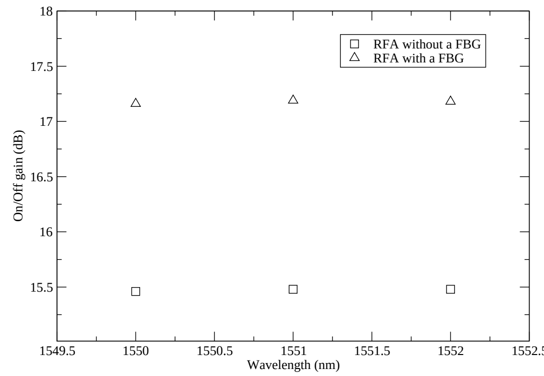

Fig. 6: Signals On/Off gain of the counter-pumped RFA with and without a FBG; L_{SMF} = 40 km; λ_p = 1450 nm; $P_{p,in}$= 600 mW; λ_s = 1550 nm, 1551 nm, 1552 nm; $S_{p,in}$= 1 mW/channel

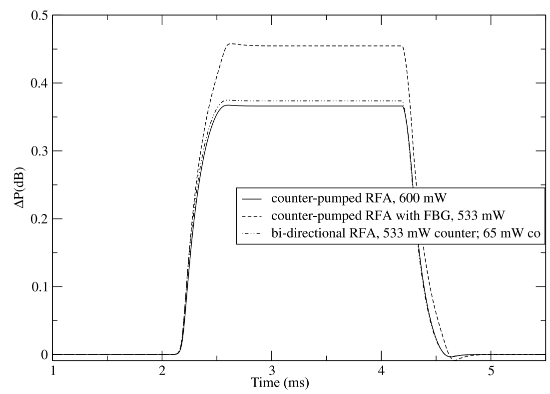

Fig. 7: Surviving channel power fluctuation as function of time when 2 out of 3 channels are add/drop; L_{SMF} = 40 km; λ_p = 1450 nm; λ_s = 1550 nm

fiber. At 4 ms the signal S_2 is added to the system, after the propagation delay we can observe that the continuous channel return to the first steady-state, with the two signals present in the fiber. The power fluctuation is about 0.01 mW. We experimentally verified that the output power of the continuous wave, channel 1555 nm, fluctuates in time due the addition/removal of 1602 nm channel. The numerical results show that our numerical model describes accurately the amplifier behavior.

IV. Study of the Pump Reflecting Raman Fiber Amplifier

To assess the impact due to the inclusion of the FBG in the amplifier configuration, we compared the behavior of the proposed pumping scheme, Fig. 1, with the traditional counter-pumped RFA and with the bi-directional RFA. We considered a pump centered at 1450 nm. The fiber used is a Single Mode Fiber with 40 km of length, with an effective area of 80 μm^2, and with an attenuation coefficient of 0.22 dB/km at the pump wavelength. We also use three channels, S_1, S_2 and S_3, with a wavelength centered at 1550 nm, 1551 nm, 1552 nm, respectively, and with 1 mW of optical power. To reproduce the add/drop in the dynamic regime, the channels are square-wave modulated with a frequency of 250 Hz.

A. Steady-state Regime

To study the increase of gain due the inclusion of a FBG in the amplifier system, we compared a counter-pumped RFA with and without a FBG. We considered one backward pump with 600 mW. Fig. 5, shows the pump power distribution in the counter-pumped amplifier with a FBG. As we can observe approximately all of the unused pump power is going to be reflected in the beginning of the amplifier fiber. Due to the FBG, extra pump power is going to be injected in the amplifier. In Fig. 6, we can observe the On/Off gain of the output signal of the amplifier with and without the FBG. When including the FBG in the amplifier, the gain increases in about 1.8 dB, when compared with the pumping scheme without a FBG.

As shown, we obtained an increase in gain, which improves the efficiency of the amplifier in the steady-state regime. If the goal is to obtain the same gain that the traditional pumping scheme, this allows the reduction of the pump power. This can be useful for developing low cost RFA.

B. Dynamic Regime

To assess the impact in the dynamic regime of including a FBG on the RFA, it is necessary to apply the same gain conditions to all the pumping schemes, therefore we reduce the input pump power from 600 mW to 533 mW in the RFA with the FBG.

Fig. 7 shows the surviving channel power fluctuation, channel S_1, as function of time, when channels S_2 and S_3 are add/drop, for the 600 mW counter-pumped RFA, 533 mW counter-pumped RFA with the FBG, and for the bi-directional RFA with 533 mW of backward pump power and 65 mW of forward pump power. The drop of the channels occurs at 2 ms and the add at 4 ms. The propagation time in the fiber is 193 μs.

For the 600 mW counter-pumped RFA we obtain a power

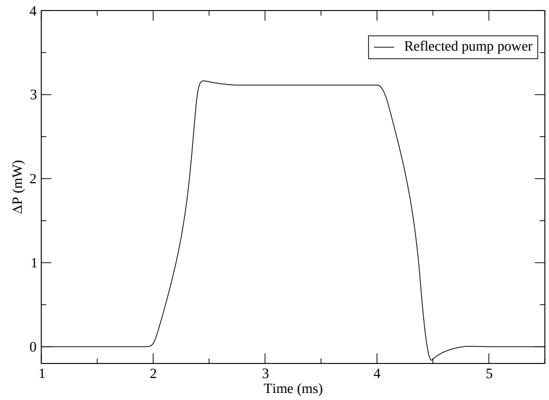

Fig. 8: Power fluctuations of the reflected pump power as function of time, when 2 out of 3 channels are add/drop; L_{SMF} = 40 km; λ_p = 1450 nm; $P_{p,in}$ = 533 mW

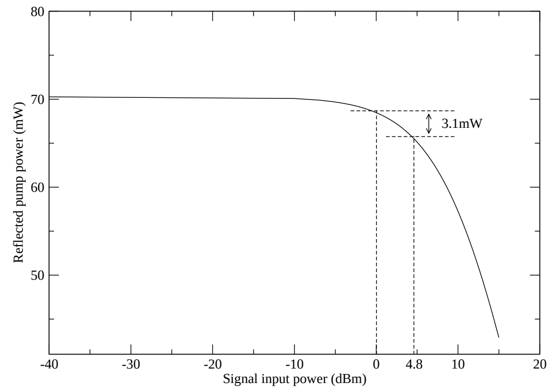

Fig. 9: Reflected pump power as function of signal input power at the beginning of the fiber; L_{SMF} = 40 km; λ_p = 1450 nm; $P_{p,in}$ = 533 mW; λ_s= 1550 nm

fluctuation of 0.36 dB and a rise time of 245 μs. For the bi-directional amplifier we obtain approximately the same results than the counter-pumped RFA, showing that the two independent pumps and the traditional counter-pumped RFA have a similar dynamic behavior. In the configuration with the FBG, we obtain 0.46 dB and a rise time of 310 μs. As we can see, despite the reduction of the input pump power, the transient response is more intense. In other hand the rise time is higher, which can be an advantage to mitigate the transient effect. The increase in the rise time can be explained by the fact that the FBG is going to re-inject the power fluctuations back into the amplifier fiber, and due to that, the channel and the pump are going to take more time to achieve a new steady-state power distribution. By observing the bi-directional RFA, we can understand that the difference of intensity between this amplifier and the amplifier with the FBG occurs due to the re-injected pump fluctuations by the FBG into the amplifier. We can observe the reflected pump power fluctuations of the amplifier with a FBG in Fig. 8. As we can see the drop of two channels is going to increase in about 3.1 mW the reflected pump power. This increase in the reflected pumo power is due to the fact that the pump suffers less depletion when the channels are dropped from the system. In Fig. 9 the reflected pump power as function of input power for channel centered at 1550 nm is shown. The reflected pump power is going to change from 65.3 mW, when all the channels are ON, to 68.38 mW, when two channels are drop from the amplifier fiber. Because of this increase in the reflected pump power, the transient response will be higher, when compared with the traditional pumping schemes.

These results show that the pump reflected Raman amplifier has a worse response to channel add/drop that the traditional pumping schemes and that could lead to strong signal degradation if this configuration is applied in dynamic optical networks.

V. Conclusion

We investigate the dynamics of a pump reflecting RFA. The theoretical analysis is based on an application of the propagation equation for the Raman amplifier, which incorporates the time and space variation. An experimental validation of the simulator was made for the steady-state and for the dynamic regime using two counter-pumped RFA configurations.

Using a FBG to reflect the unused pump power back into the amplifier has advantages in the steady-state regime, namely, an higher efficiency of the amplifier, but in the dynamic regime the amplifier has a worst response to channel add/drop. Results show that a FBG is going to intensify the surviving channel power fluctuations. An increase in the dynamic response of more than 18% was obtained, when compared with the traditional pumping scheme. We also obtain an increase in the rise time of the transient response, which can be an advantage to mitigate and control the transient response in this amplifier configuration.

To develop an efficient RFA for future dynamic optical networks it is necessary to develop a mitigation technique to apply in this configuration, in order to obtain an increase in efficiency without compromising the signal quality due to the transient effect.

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