# Comparative analysis of hybrid in line EDFA/Raman with simple Raman amplification in WDM ring PON for C+L band

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In this paper, we investigate through simulation the feasibility of amplification solutions for WDM ring PON encompassing C+L transmission bands. The system under analysis is composed by a bidirectional pump at 1480 nm with 1 W of power in each direction and 16 channels (8 C band + 8 L band). The simulation describes an 80 km WDM ring with 8 nodes in which 2 channels are added/dropped. Two scenarios were implemented, one with simple Raman amplification that considers that all the pump power travels along the ring being selected the optimal order to drop channels and another with C- band in line EDFA in the link mid length that performs and additional amplification on C band signals. The results of both approaches are compared and their suitability for practical PON is analyzed.

## 1. Introduction

The rapid growth of Internet access and services such as IP video delivery and voice-over IP (VoIP) is accelerating demand for broadband access [1] Until now, erbium-doped fiber amplifiers (EDFAs) operating in the C-band have fully used in wavelength-division-multiplexing (WDM) systems. However, since the latter is fully utilized, the needs for optical amplification technologies that provide wider optical bandwidth, namely the C +L band are under intensive research [3]. Hybrid Raman/EDFA are designed in order to maximize the span length and/or to enhance the bandwidth of the EDFA. In the context of access networks, such as WDM ring Passive Optical Networks (PON), (see Fig. 1), extended reach and high splitting ratios require amplification between Optical Line Terminal (OLT) and the Optical Network Units (ONU), performed remotely in conjunction points at the ring, referred to as the Remote Nodes (RN) [2].

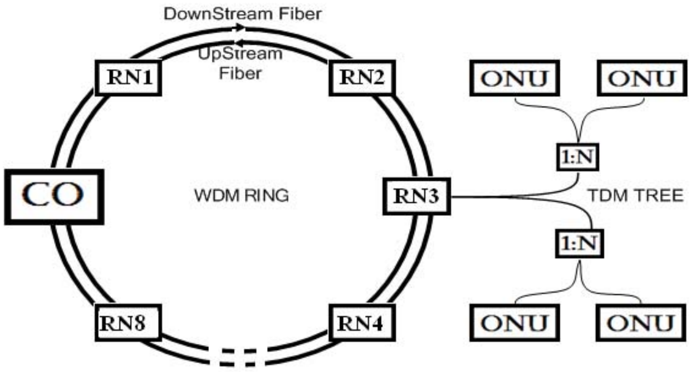


**Figure 1:** WDM ring PON scheme.

The system under analysis is a WDM ring 80 km long with 8 equally spaced nodes conceived for rural scenario. In such architecture, 2 channels are added/dropped in each remote node by a decreasing order frequency given by table 1.

Table

| | RN # | $f_1$ (THz) | $f_2$ (THz) |
|---|---|---|---|
| C band | 1 | 194.5 | 194.1 |
| | 2 | 193.7 | 191.7 |
| | 3 | 191.3 | 190.9 |
| | 4 | 190.5 | 190.1 |
| L band | 5 | 189.7 | 189.3 |
| | 6 | 188.9 | 188.5 |
| | 7 | 188.1 | 187.7 |
| | 8 | 187.3 | 186.9 |

**Table 1:** Channel dropping order along the ring (2 channels per node).

In the central office (CO), a bidirectional laser emitting at 1480 nm with total power of 2 W (1 W in each direction for normal scenario) is used to pump 16 channels spaced by 400 GHz (8 C band + 8 L band) comprised between 194.5 THz to 186.3 THz in order to avoid the current GPON DS Video overlay. The channels leave the central office with 0 dBm of optical power. The transmission has accounted for that the bypass losses are 0.53 dB for channels and 1.01 dB for the pump, being the attenuation of channels and pump are 0.20 dB/km and 0.25 dB/km, respectively. The channels drop losses are 3 dB. In the above described frame, two situations are analyzed, one with Raman amplification and the other with a hybrid amplification scheme composed by in line EDF with Raman. In latter, the EDF are only used in the half of the ring that transmits the C band channels. Hence, a 1 m long span of C band Erbium Doped Fiber (EDF) is inserted in the mid length of each link. Other scenarios with different EDF lengths are studied as well as other orders of dropping the channels. The results of both approaches are compared in terms of channel power after dropping and their suitability for practical PON are analyzed.

## 2. Raman amplification

Modeling of power evolution in Raman amplifiers, in steady state, is based on a unified treatment of information carrying signals, pumping signals. The modeling accounts the major interactions that include the pump-to-pump, channel-to-channel and pump-to-channel power transfer, attenuation. For a system with $N_p$ pumping signals, $N_s$ information carrying signals, the power evolution along the fiber distance is given by the following set of coupled differential equations:

$$\pm\frac{dP_i^{\pm}}{dz}=\left[-\alpha_i+\sum_{j=1}^{i-1}g_{ji}\left(P_j^{+}+P_j^{-}\right)-\sum_{j=i+1}^{m}\frac{\upsilon_i}{\upsilon_j}g_{ij}\left(P_j^{+}+P_j^{-}\right)\right]P_i^{\pm} \qquad (1)$$

The ± signs stand for the forward or backward propagating waves, being $\alpha_i$ the coefficients of attenuation of the $i^{th}$ wave at frequency $v_i$, The Raman gain efficiency, $g_{ij}$ [$W^{-1}m^{-1}$], accounts for the strength of the signal coupling via stimulated Raman scattering.

The simulation was carried on recurring to a semi-analytical method called Average Power Analysis (APA) [3]. This method enables us to obtain quick and accurate solutions. With a pump frequency centred at 1480 nm, the simulation has considered the Raman gain efficiency given by Fig.2. [4].

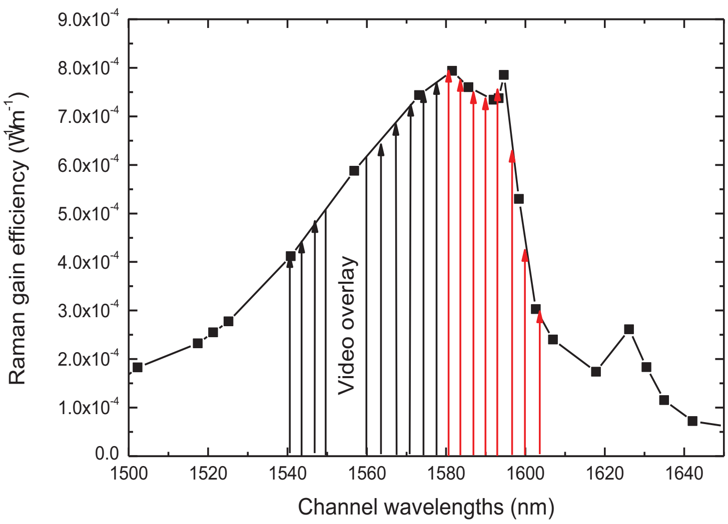


**Figure 2:** Raman gain efficiency in the considered channels bandwidth. The black and red arrows refer to C band and L band channels, respectively. The curve was obtained by interpolation of experimental data [4].

Since a high pump power is lunched into the optical fiber, stimulated Raman scattering is occurring in the channels bandwidth, as displayed in Fig. 2. The amount of gain on each channel will depend on its wavelength but also on the position it will be dropped. In the normal operation mode, the channels follow bidirectionally in the ring. The C band travel counter clock wise, going through [RN1, RN2, RN3, RN4], the L band follow the opposite direction going through [RN8, RN7, RN6, RN5]. Taking into account the dropping order defined in table 1.

## 3. Hybrid in line EDFA/Raman amplification

The modeling of hybrid EDFA/Raman involves the implementation of the Raman equations referred in section 2 but also a physical model for the EDFA. Our approach uses the set of coupled equations given by (2) and (3) for the pump and channels and ASE respectively, being the simulation also based on the APA method [5].

$$\frac{dP_k^{\pm}(z)}{dz} = \pm\left\{\left[\left(\sigma_{21}^k + \sigma_{21}^k\right)N_2(z) - \sigma_{21}^k Nt\right]\Gamma_k - \alpha_k\right\}P_k^{\pm}(z) \qquad (2)$$

where $k$ is the wavelength identifier for signals, $\sigma_{12}$ and $\sigma_{21}$ are, respectively, the stimulated emission and absorption cross sections, $\Gamma$ is the overlap integral between the dopant and the optical mode, $Nt$ is the Erbium density, $N_2$ is the upper population density.

The implementation of the set of equations (2) and (3) are also based on the APA method [ref]. The simulation has considered the following parameters: $7\times10^{24}$ *ions/m*$^3$ for Erbium density, 0.43 for overlap factor, 12 GHz for frequency strip. The fluorescence lifetime is 10 ms and the EDF fiber core radius is 1 µm, being and the initial inversion of population equal to ½. The emission and absorption cross sections are the ones given by Fig. 3.

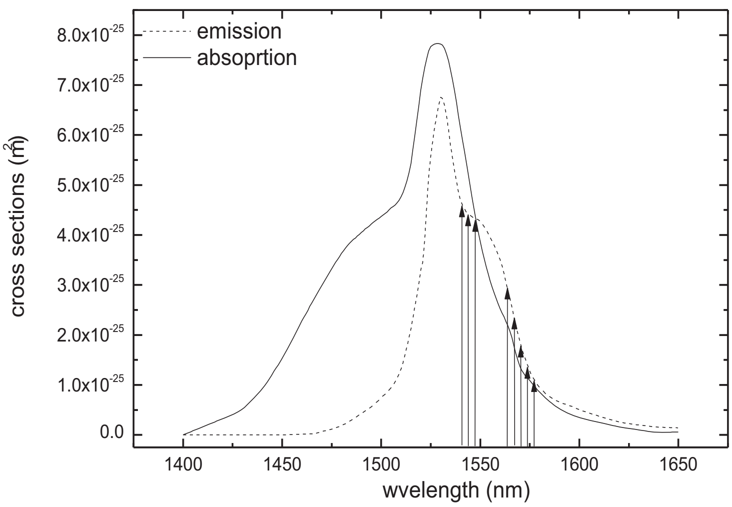


**Figure 3:** Emission and absorption cross sections given by VPI©. The black arrows refer to C band channels.

The use of in line EDFA in the C band branch of the ring enable the possibility to increase the gain in the left side of that band since Raman amplification is dominant in the L band and right side of C band. Thus, several approaches were considered: (i) a span of 1m of EDF is inserted in the middle of each link, (ii) different spans of EDF are inserted depending on the channels powers arising the previous node (this approached is called “enhanced”) and (iii) in addition to approach (ii) the channel dropping order can be also changed. The results reporting those hybrid approaches are summarized on table 2 and 3, being the power spectra results depicted on Fig. 4.

| | | Simple | Enhanced |
|---|---|---|---|
| C band | RN# | EDF length (m) | |
| | 1 | 1 | 2 |
| | 2 | 1 | 0 |
| | 3 | 1 | 2 |
| | 4 | 1 | 10 |

**Table 2:** EDF fiber span employed in the middle of each link in the simple and enhanced configuration.

| RN # | Enhanced EDF lengths | | | Enhanced EDF and dropping order | | |
|---|---|---|---|---|---|---|
| | EDF length (m) | $f_1$ (THz) | $f_2$ (THz) | EDF length (m) | $f_1$ (THz) | $f_2$ (THz) |
| 1 | 2 | 194.5 | 194.1 | 2 | 194.5 | 194.1 |
| 2 | 0 | 193.7 | 191.7 | 2 | 190.5 | 190.1 |
| 3 | 2 | 191.3 | 190.9 | 0 | 191.3 | 190.9 |
| 4 | 10 | 190.5 | 190.1 | 0.5 | 193.7 | 191.7 |

**Table 3:** Enhanced EDF fiber length employed in the middle of each link together with enhanced dropping order.

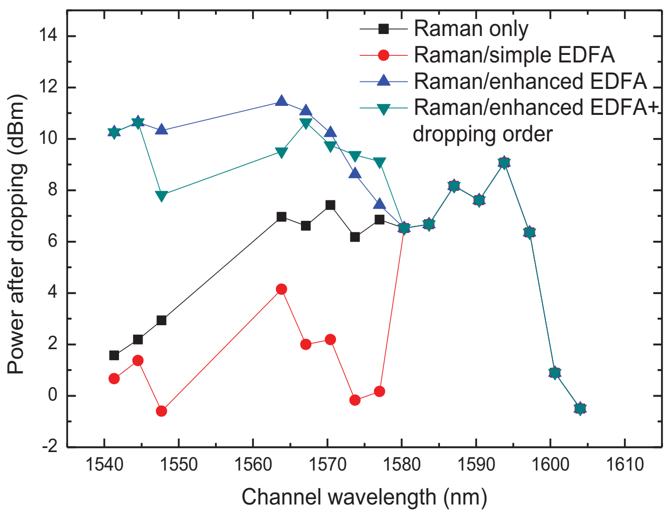


**Figure 4:** Channel power after dropping using simple and hybrid amplification. Squares: simple amplification with Raman only, circles: hybrid amplification with simple in line EDFA on the C band, upward triangles: hybrid amplification with enhanced in line EDFA enhanced EDF lengths, downward triangles: hybrid amplification with enhanced in line EDFA enhanced EDF lengths and dropping order of channels.

On looking at the power results, we notice that there is a significant amount of amplification in the range 1564-1598 nm comprised in the full width half maximum Raman gain efficiency; however the use of small lengths of EDF in the simple hybrid approach did not increase the gain in the left C band and due to the consumption of pump, the Raman gain in the right C band had also decreased. However, the use of the hybrid enhanced approach had significantly increased the left C band gain. In that approach, a 2 m span EDF is inserted in the first link to amplify the left C band, in the second link no EDF is inserted, in the third and fourth link additional EDF with 2 m and 10 m respectively are inserted. The last enhanced hybrid approach also changes the dropping order of the channels. The latter starts by dropping the first left C band channels, dropping the last C band and moving then forwardly in frequency (see table 3). This approach enables a reduction in the amount of EDF fiber used to amplify the C band, since 2.5 m are used instead of the 14 m used in the approach that keeps the channels dropping order.

## 4. Conclusion

We investigated the feasibility of several amplification solutions for a 80 km WDM ring in normal operation mode, using Raman amplification and C band in line EDFA. This survey employs 16×400 GHz channels for a rural scenario, encompassing the C+L transmission bands. The results have demonstrated that simple Raman is suitable for L band and that the C band could be amplified recurring to hybrid Raman/in line EDFA using different spans of EDF. The use of enhanced dropping order can also be a solution, because comparable results are obtain by using less EDF fiber.


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