Broadband Flat Amplification Based on Fully Double-Pass Configuration in Serial Hybrid Fiber Amplifier

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Research Article

Keywords: Double-Pass Serial Hybrid Fiber Amplifier, Erbium amplifier, Raman amplifier, Raman Scattering

Posted Date: August 2nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1701155/v1

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Broadband Flat Amplification Based on Fully Double-Pass Configuration in Serial Hybrid Fiber Amplifier

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Received: date / Accepted: date

Abstract A broadband amplification that utilizes a serial hybrid fiber amplifier is experimentally demonstrated in this paper. Two fully double-pass configurations, namely, setups A and B, are implemented. The difference between these two configurations is that the position of the two amplifiers (erbium and Raman) is swapped. These two configurations are tested under the same input parameter conditions. Two laser pump power wavelengths with a total pump power of 375 mW (1495 nm with 350 mW for Raman and 1480 nm with 25 mW for the erbium amplifier) were used. Under the optimum condition and under a small signal power of -30 dBm, a wide flatness gain bandwidth of 80 nm (1530–1610 nm) with an average gain level of 28.5 and 24 dB is achieved for setups A and B, respectively. A wide bandwidth is achieved by avoiding the amplification overlap between these two amplifiers through choosing the proper pump wavelength.

Keywords Double-Pass Serial Hybrid Fiber Amplifier · Erbium amplifier · Raman amplifier · Raman Scattering.
1 Introduction

During the 1990s, the optical amplifier was developed to address issues with optical communication systems, such as poor data degree and limited recidivist distance caused by applications that require optoelectronic amplifiers [1]. Concerns about using the communication band (C-band) have been raised [2]. This problem was addressed by creating the hybrid fiber amplifier (HFA), which integrates two or more amplifiers that have distinct operation bands. The HFA aims to enhance communication bandwidth [3-4]. It can be divided into two types based on the signal path: serial for one signal path [5-6], and parallel HFA for two signal paths [2-7]. Every setup has its own benefits and limitations. The sequential HFA has a small flat gain bandwidth but a relatively high gain and reduced noise frequency (NF). Simultaneous HFA has a more prolonged increase, flat with a lower average gain accompanied by a greater NF compared with the serial design. The double-pass setup is projected to boost primary expansion and pump conversion efficiency at a low pumping power [2]. In serial and parallel HFAs and their hybrid configuration, many double-pass HFAs have been developed [8-9]. The fundamental flaw of the erbium-doped fiber amplifier (EDFA) point is the increased pump power of 1410 mW and a decreased bandwidth gain ranging around 15 nm in signals of small-range areas. Dual-pass for comparable alignment has a strong pumping power, with an increased NF of roughly 8 dB, and distribution correction. The hybrid serial/parallel approach was developed [10-11, 12]. Although the combination method solves the dispersion problem in dual PHFA (DP-PHFA), it has several disadvantages, including high suction energy of about 800 mW, a high NF of 10 dB, and the use of triple sources of injection or pumping. The paper presents the latest DP-SHFA with an L-shaped arrangement using OptiSystem software and a sole pumping source of 1480 nm. The amplification effect is reduced by the recommended design of the combined amplifiers, exposing them to full dual-pass for the signal input in specific stages of different amplifiers, particularly in terms of the NF [14]. The field of HFA is contributed by the proposed design by adopting a new L-shaped configuration for a double-pass Raman fiber amplifier (RFA)/EDFA in the dual-pass configuration and obtaining an average gain of 23.6 dB, and a pumping power of about 300 mW. Large and small areas of the signal can experience a stretched 3 dB bandwidth gain of 60 and 65 nm, respectively. However, no gain dynamic range results were obtained. Their design shows that a gain wavelength of 1560 nm was contributed for both amplifiers; thus, a low gain dynamic range is obtained as a result of the double-pass amplification in the first amplifier. In this paper, two setups of fully double-pass configurations setups A and B are experimentally demonstrated, tested, and compared under the same amplifier parameters. Two pump power units of 1495 nm (350 mW) and 1480 nm (25 mW) are used. The wavelength of the pump power units is chosen carefully to avoid gain overlap between the two amplifiers to prevent gain saturation and achieve a wide gain dynamic range. A broad flat amplification bandwidth of 80 nm from 1530 to 1610 nm, which covers both C- and L-band regions with an average gain level of 28.5 and 24 dB, respectively, is achieved at a small input signal power of -30 dBm for setups A and B. Our results show an enhancement of 17.19% and 18.75% in average gain level and flateness gain bandwidth, respectively, as compared with a recently published paper [14].
2 Experimental setup

Figure 1 depicts the experimental setup of our proposed amplifier’s setups A and B. For setup A, the input signal is provided by a tunable source laser (TSL) with a maximum power of 14 dBm and a tunable wavelength range of 150 nm (1480–1630 nm). The provided input signal is injected into EDFA by using a 4-port circulator (Cir1) through ports 1 and 2 to experience the first erbium gain. Then, due to the optical circulator (Cir2), a second erbium gain is achieved for the input signal, and double-pass erbium gain occurs. EDFA consists of 5 m-type EDF36/6/125-3 pumped by 1480 nm pump power through a wave division multiplexer (WDM2).

![Diagram of setup A](image1)

This erbium type is selected because it can achieve gain in both conventional and long bands (C+L) to support the Raman gain at the L-band region. Therefore, because a high L-band region gain could be achieved, erbium gain clipping by reducing the erbium pump power is not required. The amplified signal is injected into the RF A via ports 2 and 3 of Cir1. Another optical circulator (Cir3) is injected at the end of the RF A to achieve double-pass amplification inside RF A. Dispersion compensation fiber (DCF) with a total length of 7 km (total loss of 4.4 dB, dispersion parameter of -110 ps/nm/km, a nonlinear coefficient of $14.5 \times 10^{-10} W^{-1}$, and effective area of 18.5 µm²) is used as a Raman gain medium pumped by a Raman pump unit of 1495 nm through WDM1. The pump wavelength is selected as 1495 nm to achieve a Raman peak gain at 1595 nm to be far from the erbium gain bandwidth, avoid gain overlap in the cascading process of the serial amplifiers and delay the saturation caused by the large input signal power. For setup B, the position of the erbium and Raman amplifier is swapped and tested under the same input parameter’s conditions to examine the performance of the proposed amplifier. At the output side, an optical spectrum analyzer (OSA) is connected to Cir1 port 4 to measure the overall gain spectrum and the noise figure of the amplified signals.

![Diagram of setup B](image2)
3 Gain and Noise Figure background

The proposed hybrid fiber amplifier is a result of combining double pass RFA in the first branch and double pass EDFA in the second branch as depicted in Fig. 1. The total gain of the proposed amplifier can be expressed as follows:

\[ G_H = \frac{P_{\text{out}}}{P_{\text{in}}} \]  

(1)

\[ P_{\text{out}} = [P_{\text{in}} \cdot \alpha_{12\text{Cir}}, G_{\text{DP-\text{RFA}}} \cdot \alpha_{23\text{Cir}}, G_{\text{DP-\text{EDFA}}} \cdot \alpha_{34\text{Cir}}] \]  

(2)

where: \( P_{\text{in}} \) (mW) is the input signal power, \( P_{\text{out}} \) (mW) is the output signal power, \( G_{\text{DP-\text{RFA}}} \) and \( G_{\text{DP-\text{EDFA}}} \) are the double pass gain factor of the Raman and Erbium, respectively, \( \alpha_{\text{Cir}} \): circulator losses. Therefore, the gain factor of the proposed Amplifier can be written as a function of \( \lambda \) as follows:

\[ G_H(\lambda) = [\alpha_{12\text{Cir}}, G_{\text{DP-\text{RFA}}}(\lambda) \cdot \alpha_{23\text{Cir}}, G_{\text{DP-\text{EDFA}}}(\lambda) \cdot \alpha_{34\text{Cir}}] \]  

(3)

In addition, \( G_{\text{EDFA}} \) and \( G_{\text{RFA}} \) were calculated in [15] and [16] respectively as the output signal power ratio to the input signal power:

\[ G_{\text{DP-\text{RFA}}} = G_{\text{FW-\text{RFA}}} + G_{\text{BW-\text{\text{RFA}}} = \frac{P_{(L)}}{P_{(0)}}} \]  

(4)

\[ G_{\text{DP-\text{EDFA}}} = G_{\text{FW-\text{EDFA}}} + G_{\text{BW-\text{EDFA}}} = \frac{P_{(L)}}{P_{(0)}} \]  

(5)

where: \( G_{\text{FW-\text{RFA}}} \) and \( G_{\text{FW-\text{EDFA}}} \) are the forward gain factor of the Raman and Erbium respectively, \( G_{\text{BW-\text{RFA}}} \) and \( G_{\text{BW-\text{EDFA}}} \) are the backward gain factor of the Raman and Erbium respectively : \( P_{(0)} \) is the inserted signal power to both of EDFA and RFA, and \( P_{(L)} \) represents the amplified signal after these two amplifiers. on the other side, the noise figure of the \( \text{DP-\text{RFA}} \) was obtained by [15]:

\[ NF_{\text{DP-\text{RFA}}}(\text{dB}) = 10 \log \frac{2P_{\text{ASE}(R)}}{h \nu G_{\text{DP-\text{RFA}}}} + \frac{1}{G_{\text{DP-\text{RFA}}}} \]  

(6)

while the noise figure in \( \text{DP-\text{EDFA}} \) was estimated by [17] as follows:

\[ NF_{\text{DP-\text{EDFA}}}(\text{dB}) = 10 \log \frac{P_{\text{ASE}(E)}}{h \nu G_{\text{DP-\text{EDFA}}}B_0} + \frac{1}{G_{\text{DP-\text{EDFA}}}} \]  

(7)

where \( P_{\text{ASE}(E)} \): EDFA noise, \( h \): Planck’s constant, \( \nu \): input signal frequency in Hz, \( B_0 \): ASE bandwidth in Hz, and \( P_{\text{ASE}(R)} \) is the noise generated in Raman amplifier.

Corresponding to Fig.1, the proposed amplifier has serial of double pass Raman-double pass Erbium- amplifier. In this context, the noise figure of the serial double pass fiber amplifier was calculated by [15] [16]:

\[ NF_{\text{SHFA}} = NF_1 + \frac{NF_2 - 1}{G_1} \]  

(8)
Therefore, the noise figure of the first amplifier branch can be written as follows:

\[
NF_{dB} = \left( 10 \log \frac{P_{ASE(E)}}{h \nu G_{DP-EDFA} B_0} + \frac{1}{G_{DP-EDFA}} \right) + \left( 10 \log \frac{2P_{ASE(R)}}{h \nu G_{DP-RFA} B_0} + \frac{1}{G_{DP-RFA}} \right) - 1
\]

(9)

4 Results and Discussions

Figure 2 shows the optimization of the overall emission peak bandwidth with the variation of the erbium pump power and maximum Raman pump power of 350 mW, as illustrated in Figure 2a. The emission peak bandwidth was measured in the absence of the input signal power provided by TLS. The optimum bandwidth was chosen as the erbium pump power so that the overall emission peak difference should not exceed 3 dB. With the erbium pump power varied from 10 to 50 mW with a 5mW step, the optimum erbium pump power of 25 mW was observed. Figure 2b illustrates the emission peak power of setups A and B at the optimal pump power values for both pump units (1495 nm with 350 mW for Raman and 1480 nm with 25 mW for the erbium amplifier). The importance of the emission peak is that it reflects the overall gain flatness of the amplifier. Both setups show a wide flatness emission peak, with only a slight increment in setup A. This increment can be attributed to the double-pass Raman gain that slightly saturates the erbium gain at the C-band region in setup B.

Figure 3 shows the overall gain spectrum and the corresponding noise figure of the proposed setups A and B. At a small input signal power of -30 dBm (Figure 3a), both setups show a wide flatness gain bandwidth of 80 nm from 1530 to 1610 nm. A high average gain level of 28.5 dB was achieved for setup A, while an average gain level of 24 dB was recorded for setup B. As mentioned in Figure 2b, saturation
happened in setup B in the erbium emission peak, which directly affects the erbium peak gain in the C-band region and the tail gain of the erbium in the L-band region and subsequently reduced the gain in setup B. At a small input signal power, the flatness gain bandwidth and average gain improved by 29.41% and 17.5%, respectively, as compared with other results [14]. Lower noise figure values were achieved in the C-band region for setup A, being almost 4 dB lower than the noise figure values of setup B as a result of the higher gain level achieved in setup A. For the L-band region, almost the same noise figure values were obtained for both setups because the Raman gain is more effective in this optical band. For both setups, no Raman gain saturation occurred. The overall gain saturation is also tested under a high input signal power of -10 dBm. Both setups show the same flatness gain bandwidth of 80 nm (1530-1610 nm) but with a lower average gain level of 15 and 12 dB for setups A and B, respectively, as depicted in Figure 3b. In addition, almost the same noise figure values were recorded for both amplifier’s setups but with higher values compared with values at a small input signal power regime due to the saturation effect. Under a large input signal power regime, our results illustrate an enhancement of 18.75% in flatness gain bandwidth compared with the results of [14].

More results were obtained for both the amplifier’s setups to show the effect of the input signal power variations on the overall gain spectrum, as illustrated in Figures 4a and 4b. The input signal power varied from -30 dBm to -5 dBm. Setup A (Figure 4a) shows higher average gain levels than those of setup B (Figure 4b), especially at small input signal power values until -15 dBm. For input signal power values of -10 and -5 dBm, both amplifier’s setups exhibited almost the same average gain level due to the deeper saturation in setup A compared with that in setup B.

The gain dynamic range was measured for setups A and B, as depicted in Figures 5a and 5b. Two input signal power wavelengths of 1550 nm (Figure 5a) and 1600 nm (Figure 5b) were selected as the emission peaks of the erbium and Raman amplifiers. The results were used to evaluate the input power range for the two proposed setups. At 1560 nm, setup A shows early saturation, and the gain dynamic range was saturated at -28 dBm while the gain dynamic range was saturated at -15 dBm for setup

Fig. 3: Overall gain and noise figure a) small input signal power of -30 dBm. b) large input signal power of -10 dBm
B, which is a larger range at about 13 dB compared with that for setup A. For setup A, in which the erbium amplifier is used first, the inserted signal experiences a high single-pass gain that highly saturates the double-pass gain in the erbium amplifier. Therefore, deep overall gain saturation occurred. In the condition where the Raman amplifier was used, the inserted signal is first inserted into the Raman amplifier for double-pass amplification. No saturation occurs in the Raman amplifier because the Raman amplifier can be saturated only at a high input signal power larger than -5 dBm and because the 1550 nm wavelength is slightly far from the amplification peak of the Raman amplifier. As a result, the amplified signal that is inserted into erbium gain can result in erbium gain saturation. Therefore, no deep saturation occurred in the second round of the erbium gain. For the second input signal wavelength of 1600 nm (Figure

![Fig. 4: Overall gain and noise figure at different input signal power. a) setup A, b) setup B.][5b], setup A also exhibits an early saturation value at an input signal power of -27 dBm compared with -13 dBm in setup B. Even though this wavelength is far from the peak gain of the erbium, it is still the double-pass erbium tail gain that can result in faster overall gain saturation. The highly amplified signal after the double-pass amplification in the Raman amplifier can deeply saturate the erbium gain because the signal wavelength is located at the Raman peak gain. Therefore, even though deep satura-
tion occurred in erbium gain, no saturation took place in the overall gain because the erbium gain has a higher gain level than Raman gain. The early saturation of setup A makes it infeasible for real application because no flatness gain could be achieved for the inserted signal power greater than -27 dBm. In reference to the recently published work presented by[14], no gain dynamic range results were obtained. More results were obtained to show the performance of the proposed amplifiers (setups A and B). The input and the amplified signals were recorded for these setups at C-band (1550 nm) and L-band (1600 nm) regions as depicted in Figures 6(a, b, c, and d). The results illustrate high gain level and optical signal-to-noise ratio for both setups.

Fig. 6: Output spectrum of the input and the amplified signals at two wavelength bands (C- and L-band regions).

5 COMPARISON

To assess the performance of the proposed amplifier setups, a comparison is performed between our results and those of different double-pass configurations presented by [8][9][10], [14], as illustrated in Table 1.

The comparison is first performed with a double-pass serial hybrid fiber amplifier (DP-SHFA)[8], which has a lower average gain level, narrow flatness gain for both small and large input signal powers, and large pump power value, as presented by[8]. Second, a DP-PHFA [9] is contrasted with our results and showed a higher
Table 1: Evaluation of the Proposed System’s Performance in Relation to Previous Work [8,9,10,14]

<table>
<thead>
<tr>
<th>Reference</th>
<th>Amplifier Design</th>
<th>Pump Power (mW)</th>
<th>Gain (dB)</th>
<th>G.B. Small Signal (nm)</th>
<th>G.B. Large Signal (nm)</th>
<th>RF A Length (m)</th>
<th>EDF A Length (m)</th>
<th>NF av. (dB)</th>
<th>No. of Pumping Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>[8]</td>
<td>DP-SHF A</td>
<td>1410</td>
<td>17.2</td>
<td>15</td>
<td>35</td>
<td>5.1</td>
<td>3.5</td>
<td>28</td>
<td>1 at 1411 nm</td>
</tr>
<tr>
<td>[9]</td>
<td>DP-SHF A</td>
<td>650</td>
<td>22.5</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>3</td>
<td>8</td>
<td>1 at 1400 nm</td>
</tr>
<tr>
<td>[10]</td>
<td>DP-CSPHF A</td>
<td>800</td>
<td>22.6</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>3</td>
<td>10.6</td>
<td>1 at 1410/1480/1495 nm</td>
</tr>
<tr>
<td>[14]</td>
<td>FDP-SHF A</td>
<td>300</td>
<td>23.6</td>
<td>60</td>
<td>65</td>
<td>65</td>
<td>3</td>
<td>7</td>
<td>3 pumps (1 at 1410/1495)</td>
</tr>
<tr>
<td>Our work</td>
<td>DP-SHF A</td>
<td>375</td>
<td>28.5</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>3</td>
<td>7</td>
<td>4 pumps (1 at 1410/1495)</td>
</tr>
</tbody>
</table>

pump power, lower average gain level, and narrow flatness gain bandwidth. Third, a combination of double-pass serial parallel hybrid fiber amplifier (DP-SPHFA) [10] is collated with our results, which showed a lower pump power, the same flatness gain bandwidth, and lower noise figure values. Finally, a comparison is performed with FDP-SHFA [14]. Our results are better in terms of wider flatness gain bandwidth for small and large input signal powers and higher average gain level. In addition, no gain dynamic range results were obtained by [14]. If a gain dynamic range in our design (setup A) is achieved in the same way as in the configuration presented by [14], then no gain dynamic range can be obtained even though those two different pump power wavelengths were chosen to avoid overlap between the two amplifiers. Therefore, the amplifier’s location needs to be swapped (setup B) to achieve a wide gain dynamic range.

6 Conclusion

The flatness gain bandwidth is improved via a double pass for erbium and Raman amplifiers. The main point behind such wide flatness gain is the optimum pump power wavelengths that were chosen for these two amplifiers to prevent the overlapping of the amplification’s bandwidth. For both setups, a broadband flat gain bandwidth of 80 nm from 1530 to 1610 nm, which covered both the conventional and long bands (C+L), is achieved. For setup A, an average gain level of 28.5 and 17.5 dB is recorded at small and large input signal powers of -30 and -10 dBm, respectively. At the same input power values, setup B presented an average gain level of 25.5 and 11.5 dB. As a result of the early saturation power of -27 dBm in setup A, this setup is unsuitable for real-time application. These results show that the flat gain bandwidth improved by about 25% and 18.75% compared with the results provided by [8]. In terms of average gain level, our proposed setup exhibits an enhancement of 17.19% and 18.75% compared with the average gain level and gain flatness gain, respectively, provided by [14] at a small input signal power.

References


