Broadband flat amplification based on fully double-pass configuration in serial hybrid fiber amplifier

Ali Yaseen Ali\textsuperscript{1,2} · Mohammed Kamil Salh Al-Mashhadani\textsuperscript{3} · Thamer Fahad Al-Mashhadani\textsuperscript{4} \textsuperscript{✉} · Mohammed K. Awsaj\textsuperscript{5} · Yassine Bouteraa\textsuperscript{1,6}

Received: 27 May 2022 / Accepted: 20 September 2022 / Published online: 5 October 2022 © The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

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. In addition, a gain dynamic range values of 3 dB and more than 15 dB were recorded for setup A and B respectively.

Keywords Double-pass serial hybrid fiber amplifier · Erbium amplifier · Raman amplifier · Raman scattering

\textsuperscript{✉} Thamer Fahad Al-Mashhadani
thamer.fahad@uoa.edu.iq

1 Control and Energy Management Laboratory (CEM Lab), Ecole Nationale d Ingenieurs de Sfax (ENIS), Institut Superieur de Biotechnologie de Sfax (ISBS), University of Sfax, Sfax 3038, Tunisia
2 Department of Petroleum Systems Control Engineering, Tikrit University, Saladdin, Iraq
3 Department of Electrical Engineering, Tikrit University, Saladdin, Iraq
4 Department of Computer Engineering Techniques, Al-Maarif University College, Ramadi, Iraq
5 Department of Electrical Engineering, Al-Anbar University, Ramadi, Iraq
6 Department of Computer Engineering, College of Computer Engineering and Sciences, Prince Sattam Bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia
1 Introduction

During the 1990s, the optical amplifier was developed to address issues with optical communication systems, such as low bit rate and limited repeater distance caused by applications that require optoelectronic amplifiers (Becker et al. 1999). Concerns about using the communication band (C-band) have been raised (Abass et al. 2014). 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 (Liaw et al. 2006; Mahran and Aly 2016). It can be divided into two types based on the signal path: serial for one signal path (Ali et al. 2015, 2020), and parallel HFA for two signal paths (Abass et al. 2014; Ali et al. 2014). Every setup has its own benefits and limitations. The serial HFA has a small flat gain bandwidth but a relatively high gain and reduced noise frequency (NF). Parallel 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 (Abass et al. 2014). In serial and parallel HFAs and their hybrid configuration, many double-pass HFAs have been developed (Seo et al. 2007; Ali et al. 2020). 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 (Gurkaynak 2021; Abass et al. 2018; Ali et al. 2019; Abass et al. 2018). 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 (Khudhair et al. 2021). 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 flatness gain bandwidth, respectively, as compared with a recently published paper (Khudhair et al. 2021).
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 and minimum power of 14 dBm and −14 dBm respectively and a tunable wavelength range of 150 nm (1480–1630 nm). The injected signal power is varied via variable optical attenuator (VOA) at fixed Bp power of 0 dBm. 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).

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 RFA via ports 2 and 3 of Cir1. Another optical circulator (Cir3) is injected at the end of the RFA to achieve double-pass amplification inside RFA. 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 μm$^2$) 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.

![Fig. 1 Experimental setup of the proposed amplifier; a: setup A, b: setup B](image-url)
3 Gain and noise figure background

The proposed hybrid fiber amplifier is a result of combining of 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:

$$G_H = \frac{P_{\text{out}}}{P_{\text{in}}}$$

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

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

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

In addition, $G_{\text{EDFA}}$ and $G_{\text{RFA}}$ were calculated in Becker et al. (1999) and Agrawal (2005) respectively as the output signal power ratio to the input signal power:

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

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

where: $(G_{\text{FW-RFA}})$ and $(G_{\text{FW-EDFA}})$ are the forward gain factor of the Raman and Erbium respectively, $(G_{\text{BW-RFA}})$ and $(G_{\text{BW-EDFA}})$ 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 $\text{DP-RFA}$ was obtained by Becker et al. (1999):

$$NF_{\text{DP-RFA}}(dB) = 10 \log \frac{2P_{\text{ASE,R}}}{\hbar G_{\text{DP-RFA}}B_0} + \frac{1}{G_{\text{DP-RFA}}}$$

while the noise figure in $\text{DP-EDFA}$ was estimated by Bristiel et al. (2004) as follows:

$$NF_{\text{DP-EDFA}}(dB) = 10 \log \frac{P_{\text{ASE,E}}}{\hbar G_{\text{DP-EDFA}}B_0} + \frac{1}{G_{\text{DP-EDFA}}}$$

where $P_{\text{ASE,R}}$: EDFA noise, $\hbar$: Planck’s constant, $v$: input signal frequency in Hz, $B_0$: ASE bandwidth in Hz, and $P_{\text{ASE,E}}$ 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 Becker et al. (1999), Agrawal (2005):

$$NF_{\text{SHFA}} = NF_1 + \frac{NF_2 - 1}{G_1}$$
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 Fig. 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 (Fig. 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 Fig. 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 (Khudhair

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

Fig. 2 (a) Emission peak at maximum Raman pump and at different erbium pump powers. (b) emission peak at the optimum pump powers

 Springer
et al. 2021). 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. The high noise figure values were recorded in setup B in which the tail gain of the double pass Raman at C-band region caused Erbium gain saturation that resulted in high noise figure values compared to setup A in which the injected signal is directly inserted to erbium amplifier.

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 Fig. 3b. In addition, almost the same noise figure values were recorded for both the 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 Khudhair et al. (2021). For Fig. 3a, at small input signal power, no gain saturation was recorded for both of erbium and Raman gain. A high overall gain level was recorded in setup A as compared to setup B. The reason behind that can be attributed to the erbium gain saturation due to the double pass Raman gain (tail gain at C-band region) in setup B. While at large input signal power of −10 dBm, erbium gain suffers from deep saturation in both of setup A and B compared to Raman gain which almost not saturated in setup A. In another word, −10 dBm caused an erbium gain saturation in the single pass amplification stage. Deep gain saturation is caused by the double erbium gain process even if the erbium was inserted in the first amplifier stage (setup A). On the other side, no more erbium gain saturation can be achieved by the double pass Raman gain at the C-band region (tail gain) in setup B. Therefore, the overall gain level at such input signal power is mainly dependent on the Raman gain saturation for these two setups. Thus, slightly higher overall gain level was recorded for setup B as the Raman gain saturation is lower since the input signal power is directly injected into the Raman amplifier.

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 Figs. 4a and 4b. The input signal power varied from −30 dBm to −5 dBm. Setup A (Fig. 4a) shows higher average gain levels than those of setup B (Fig. 4b), especially at small input power.
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 Fig. 5a and b. Two input signal power wavelengths of 1550 nm (Fig. 5a) and 1600 nm (Fig. 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 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.

Fig. 4 Overall gain and noise figure at different input signal power. (a) setup A, (b) setup B

Fig. 5 Gain dynamic range at two wavelength bands (a) at 1550 nm C-band (b) at 1600 nm L-band
For the second input signal wavelength of 1600 nm (Fig. 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 saturation 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 Khudhair 2021, no gain dynamic range results were obtained. More results were obtained to show the performance of the proposed amplifiers (setups A and B). Wider gain dynamic range more than 15 dB was obtained for setup B compared to 3 dB in setup A due to the deep saturation of the erbium gain at 1550 nm (Fig. 5a) and the double pass erbium gain in L-band region at 1600 nm can be resulted in overall gain saturation early.

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 Fig. 6a, 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 Seo et al. (2007); Ali et al. (2020); Gurkaynak (2021), Khudhair et al. (2021), as illustrated in Table 1.

The comparison is first performed with a double-pass serial hybrid fiber amplifier (DP-SHFA) (Ali et al. 2020), 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 (Ali et al. 2020). Second, a DP-PHFA (Ali et al. 2020) is contrasted with our results and showed a higher pump power, lower average gain level, and narrow flatness gain bandwidth. Third, a combination of double-pass serial parallel hybrid fiber amplifier (DP-SPHFA) (Gurkaynak 2021) 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(Khudhair et al. 2021). 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 Khudhair et al. (2021). If a gain dynamic range in our design (setup A) is achieved in the same way as in the configuration presented by Khudhair et al. (2021), 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 (Ali et al. 2020). 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 Khudhair 2021 at a small input signal power.
Table 1  Evaluation of the Proposed System’s Performance in Relation to Previous Work (Seo et al. 2007; Ali et al. 2020; Gurkaynak 2021; Khudhair et al. 2021)

| Reference           | Amplifier Design | Pump Power (mW) | G.av. (dB) | G.B. Small Signal (nm) | G.B. Large-Signal (nm) | RFA Length (km) | EDFA Length (m) | NFav. (dB) | No. of Pumping Sources |
|--------------------|------------------|-----------------|------------|-----------------------|------------------------|------------------|-----------------|------------|------------------------|
| Seo et al. (2007)  | DP-SHFA          | 1410            | 17.2       | 15                    | 55                     | 1.3              | 3               | 6.8        | 1 at 1411 nm           |
| Ali et al. (2020)  | DP-SHFA          | 650             | 22         | 60                    | 60                     | 7                | 3               | 8          | 1 at 1480 nm           |
| Gurkaynak (2021)   | DP-CSPHFA        | 800             | 22.5       | 80                    | 90                     | 7                | 3               | 10.6       | 3 at 1410/1480/1495 nm |
| Khudhair et al. (2021) | FDP-SHFA      | 300             | 23.6       | 60                    | 65                     | 7                | 3               | 7          | 1 at 1480 nm           |
| Our work           | DP-SHFA          | 375             | 28.5       | 80                    | 80                     | 7                | 5               | 4          | 2 pumps (1 at 1410/1 at 1495) |
Funding  There is no funding for this research.

Data availability  All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest  The authors declare that there are no conflicts of interest related to this article.

References

Abass, A.K., Abdul-Razak, M.J., Salih, M.A.: Gain characteristics for C-band erbium doped fiber amplifier utilizing single and double-pass configurations: a comparative study. Eng. Tech. J. 32, 2165–2173 (2014)

Abass, A.K., Ali, M.H., Al-Hussein, S.A.A.: Optimization of hybrid fiber amplifier utilizing combined serial-parallel configuration. IOP Conf. Ser. Mater. Sci. Eng. 454, 1757 (2018)

Abass, A.K., Ali, M.H., Al-Hussein, S.A.A.: Wideband flat-gain hybrid fiber amplifier utilizing combined serial-parallel configuration. Int. J. Nanoelectron. Mater. 11, 17–22 (2018)

Agrawal, G.P.: Raman Amplification in Fiber Optical Communication Systems. Academic Press, 33–102 (2005)

Ali, M.H., Abdullah, F., Jamaludin, M.Z., Al-Mansoori, M.H., Al-Mashhadani, T.F., Abass, A.K.: Simulation and experimental validation of gain-control parallel hybrid fiber amplifier. J. Opt. Soc. Korea. 18, 657–662 (2014)

Ali, M.H., Abdullah, F., Jamaludin, M.Z., Al-Mansoori, M.H., Abass, A.K., Al-Mashhadani, T.F.: Effect of cascading amplification stages on the performance of serial hybrid fiber amplifier. Fiber Integr. Opt. 34, 157–170 (2015)

Ali, M.H., Abass, A.K., Abd Al-Hussein, S.A.: 32 Channel×40 Gb/s WDM optical communication system utilizing different configurations of hybrid fiber amplifier. Opt. Quantum Electron. 51, 1–8 (2019)

Ali, M.H., Ali, A.H., Abdulsatar, S.M., Saleh, M.A., Abass, A.K., Al-Mashhadani, T.F.: Pump power optimization for hybrid fiber amplifier utilizing second order stimulated Raman scattering. Opt. Quantum Electron. 52, 15–16 (2020)

Ali, M.H., Abdullah, F., Al-Mashhadani, T.F.: Gain-control technique in double-pass parallel hybrid fiber amplifier. Opt. Quantum Electron. 52, 1–7 (2020)

Becker, P.C., Olsson, N.A., Simpson, J.R.: Erbium-Doped Fiber Amplifiers. Academic Press. 131–152 (1999)

Becker, P. M., Olsson, A. A., Simpson, J. R.: Erbium-doped fiber amplifiers: fundamentals and technology. Elsevier, (1999)

Bristiel, B., Gallion, P., Jaouen, Y., Pincemin, E: Abd, Intrinsic noise figure derivation for fiber Raman amplifiers from equivalent noise figure measurement. Proceedings of the Lightwave Technologies in Instrumentation and Measurement Conference. 135–140 (2004)

Gurkaynak, I.A., et al.: Widedly flatness gain bandwidth with double pass parallel hybrid fiber amplifier. Opt. Quantum Electron. 53, 1–11 (2021)

Khudhair, A.A., Ali, M.H., Abass, A.K.: Wideband full double-pass serial hybrid fiber amplifier utilizing L-shape configuration. Appl. Opt. 60, 10680 (2021)

Liaw, S.K., Ho, K.P., Huang, C.K., Chen, W.T., Hsiao, Y.L., Lai, I.G.: Investigate C+L band EDFA/Raman amplifiers by using the same pump lasers. Proc. 9th Jt. Conf. Inf. Sci. JCIS. 2–5 (2006)

Mahran, O., Aly, M.H.: Performance characteristics of dual-pumped hybrid EDFA/Raman optical amplifier. Appl. Opt. 55, 22–26 (2016)

Seo, H.S., Alm, J.T., Park, B.J., Chung, W.J.: Double-pass resonant Er-Raman amplifier. Electron. Lett. 43, 801–802 (2007)

Publisher's Note  Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.