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RESEARCH ARTICLE

An efficient wide flatness gain bandwidth with parallel hybrid fiber amplifier

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Abstract

In this article, we experimentally propose an efficient wide flat gain bandwidth with a parallel hybrid fiber amplifier. The setup includes parallel amplifier branches. In the first branch, serial erbium-doped and Raman fiber amplifiers are used. In the second branch, only a Raman fiber amplifier is used. Three Raman pump power units (i.e., 1410, 1480, and 1495 nm) are used to achieve Raman gain at different optical communication bands. At optimum pump powers and at a small-signal power of −30 dBm, an average gain of 18.5 dB with a maximum gain variation of 3 dB and a gain flatness bandwidth of 83 nm, that is, from 1527 to 1610 nm, is achieved. This gain flatness is expanded to 92 nm (1525–1617 nm) at a large input signal power of −5 dBm with an average gain level of 13 dB. In our proposed amplifier, the Raman amplification peaks (1510 and 1595 nm) are chosen to be far from the erbium amplification peak (1530–1570 nm) in order to avoid the overlapping and the saturation in the first amplifier branch. Therefore, due to such wavelength optimization in addition to the recycling the residual Raman pump power, a wide flatness gain bandwidth is achieved for both of low and large input signal powers.

KEYWORDS
EDFA, multi-Raman pump, parallel HFA, RFA

1 | INTRODUCTION

Hybrid fiber amplifiers (HFAs) that combine erbium-doped fiber amplifier (EDFA) and Raman fiber amplifier (RFA) were implemented in previous studies to enhance the performance of optical amplifiers in many parameters, namely, decrease the optical fiber nonlinearities, increase the optical span length, increase the overall gain bandwidth, and enhance the pump power efficiency.[1,2] Generally, two HFA approaches have been designed: serial HFA (SHFA),[3–10] and parallel HFA (PHFA).[11–18] The optical signal propagation path is the main difference between these two amplifier approaches. The SHFA usually has one signal path in which the input signal can experience two amplification stages from two different amplifiers, namely, EDFA and RFA. Therefore, the amplified signal from the first stage is inserted to the second stage as an input signal power. In this amplifier type, a high gain level and an acceptable noise figure could be achieved. However, this type of HFA is mainly degraded by narrow gain flatness and low gain dynamic range. A wide bandwidth of 76 nm from 1531.5 to 1607.5 nm was reported in a previous study.[6] However, three amplification stages with five laser pumps (one for EDFA and four for RFA) were utilized in addition to the gain equalizer. Another SHFA with a double-pass configuration was reported.[7] A wide gain flatness of 70 nm (1530–1600 nm) was achieved at the expense of a high pump power of 1.4 W. An array of complex fiber Bragg grating in a SHFA was proposed in Reference 8. Up to 65 nm of bandwidth from 1530 to

1595 nm and a small gain variation of 0.2 dB were achieved. A partial double-pass EDFA with hybrid gain medium of hafnium bismuth erbium co-doped fiber (HB-EDF) and Zirconia-Yttria-Aluminum co-doped erbium fiber was reported by Reference 9. Up to 17.2 dB gain level over a 55 nm from 1540 to 1595 nm at large input signal power of −10 dBm was achieved. However, a degradation was clear at low input signal power of −30 dBm and no flat gain bandwidth was observed. A triple-pass hybrid optical fiber amplifier in a dual-stage configuration was proposed by Reference 10. Up to 45 nm flatness gain bandwidth from 1555 to 1600 nm with a gain level of 19 dB was recorded at large input signal power of −10 dBm. However, no flatness gain bandwidth was observed at low input signal power of −30 dBm. Unlike the SHFA, the input signal in the PHFA is divided into two different paths according to either its power or wavelengths. Using this parallel configuration, the gain of each branch is easy to control individually because of the absence of the cascading effect. A single pump of 1480 nm with a percentage ratio of 29:1 for the RFA and the EDFA was utilized in the PHFA.[11] In this configuration, the C-band region in which the EDFA is responsible for showing an average gain of 14 dB, while the RFA presents an average gain of 13.6 dB in the L-band region. After 1-year, the same authors proposed the PHFA, which utilizes the power equalization technique.[12] In this new configuration, the gain variation is reduced from 9.8 to 0.5 dB. The optimal pump percentage ratio is 10:1 for the RFA and the EDFA. In addition, the pumping efficiency is enhanced by using two pump reflectors. For these two PHFA configurations, the input signal is divided according to its wavelength into the C-band and L-band regions. However, large input signal power from the early gain saturation in the EDFA, which exceeds −10 dBm, illustrates the degradation in both gain flatness and level. A signal pass PHFA approach in which the input signal is divided according to its power was proposed in Reference 13. The input signal power ratios are controlled via a variable optical attenuator (VOA). Up to 60 nm of flatness gain bandwidth from 1530 to 1590 nm and an average gain of 14 dB are achieved. Recently, the same gain control technique was used in a double-pass PHFA.[14] The average gain increased from 14 to 22.8 dB (38.5%) at the same flatness gain bandwidth (1530–1590 nm). In addition, the pump power used was reduced from 800 to 650 mW (18.7%). However, different input signal ratios are needed for small and large input signal powers. In addition, for the dispersion compensation issue in the dense wavelength division multiplexing (DWDM) communication system, the EDFA branch has no compensation dispersion. Dual-stage double-pass HB-EDFAs in conjunction with parallel configuration was presented by Reference 15. Wide flatness gain of 80 nm (1525–1605 nm) with a gain level of 12.1 dB was recorded at large input signal power of −10 dB. However, since large input signal power is used, the proposed scheme was under deep saturation. Therefore, high noise figure value of 11.8 dB was obtained. In addition, the flatness gain bandwidth was limited to 35 nm (1525–1560 nm) at small input signal power of −30 dBm.

To overcome the dispersion compensation problem in the EDFA branch, a dispersion compensation fiber (DCF) is added to the EDFA branch as an additional RFA. Abass et al. (2018) reported a simulation of a new PHFA structure in which a total pump power of 1.1 W for 1480- and 1495-nm pump power units is used. However, a limited flatness gain bandwidth of 62.5 nm (1530–1592.5 nm) and a low average gain of 13.38 dB are produced.[16] A control technique method was implemented by controlling the input signal ratio. A fixed input signal power ratio of 0.7 was inserted into two amplifier branches for small and large input signal powers. However, a limited average gain level of 16 dB was achieved, and a multiple pump power of 1.4 W (i.e., 800 mW for 1480 nm, and 1495 nm with 600 mW) was utilized. In addition, the flatness gain level achieved was limited to 65 nm (1530–1595 nm) at the small input signal region, and the gain flatness bandwidth was reduced to 45 nm (1550–1595 nm) at the large input signal power.[17] The same design parameters were adopted in Reference 18 based on 32 input channels. The simulation results show the same amplifier performance presented by Reference 17 in both input signal power regions. In this article, a PHFA is experimentally presented. A fixed input signal power ratio (50:50) is inserted in both amplifier branches. The technique that recycles the Raman residual pump is used to enhance the pumping efficiency and the optical signal-to-noise ratio (OSNR) of the amplified signal. A wide gain flatness of 83 nm (1527–1610 nm) and an average gain of 18.5 dB at a low input signal power of −30 dBm are presented. This flatness bandwidth is expanded to 92 nm (1525–1617 nm) at a high input signal power of −5 dBm. The Raman pump power wavelengths are carefully chosen at 1410 and 1495 nm in the first amplifier branch which provided Raman peak gain bandwidth at 1510 and 1595 nm. These two Raman peaks are a way from the erbium peak gain at the C-band region. Therefore, no overlapping and no saturation could be taken the wide flatness gain can be achieved for both signal power regions.

2 | EXPERIMENTAL SETUP

Figure 1 shows the experimental setup of the proposed PHFA amplifier. The input signal power is delivered by a tunable laser source (TLS) with a wavelength range of 1480 nm to 1650 nm and a maximum signal power of 14 dBm. The signal delivered from the TLS is attenuated by a VOA. An optical circulator is connected directly after the VOA to extract the residual pump of the EDFA and prevent any feedback to the TLS. A 3-dB coupler is utilized to split

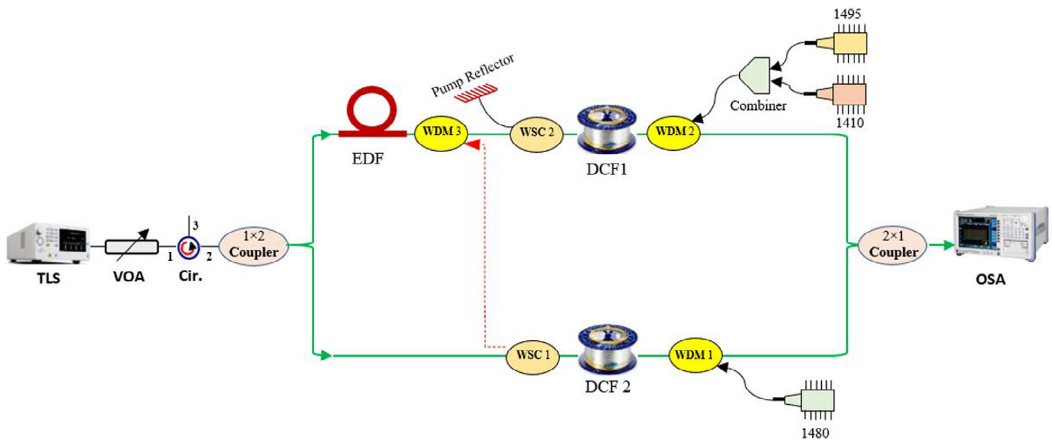

FIGURE 1 Experimental setup of the proposed PHFA amplifier. PHFA, parallel hybrid fiber amplifier [Color figure can be viewed at wileyonlinelibrary.com]

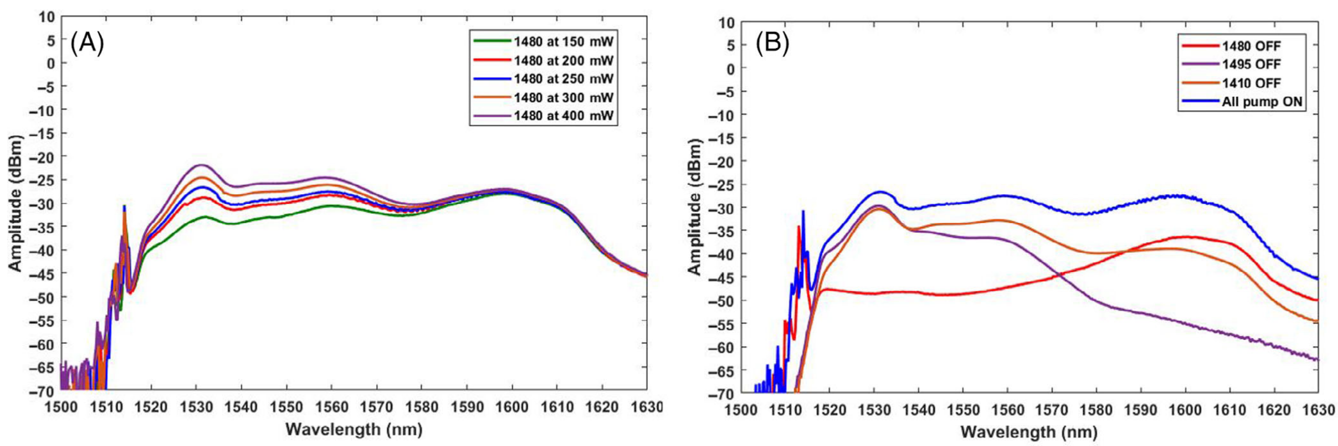

FIGURE 2 (A) ASE at 1410 and 1495 pump power of 475 mW and at different 1480 pump powers. (B) ASE of the proposed PHFA amplifier at optimal pump powers with different conditions. ASE, amplified spontaneous emission; PHFA, parallel hybrid fiber amplifier [Color figure can be viewed at wileyonlinelibrary.com]

the input signal power into two equal parts to be inserted into the two amplifier branches. In the first branch, 3 m of EDF (Er3+ ion concentration: 440 ppm, Er-doped core radius: 1.9 μm, and cut-off wavelength: 300 nm), which is pumped by the residual pump of the 1480 nm pump power extracted by the wave selective coupler (WSC1), is used as an EDFA; 7 km of DCF (total loss of 4.4 dB, dispersion parameter of −110 ps/nm/km, a nonlinear coefficient of 14.5×10^{-10} W^{-1} and effective area of 18.5 μm^2), which is pumped by two Raman pump units (1410 and 1495 nm with 475 mW for both), is used as an RFA. These two Raman pump units are important in achieving a good tail gain at the C-band region corresponding to 1410 nm and the L-band region achieved by 1495 nm. The residual pump power of these two units is extracted via the WSC2 and then recycled into a DCF via the pump reflector. On the other side, 7 km of DCF with the same parameters, which is pumped by 1480 nm, is implemented as an RFA in the second branch. The inserted signal part at the first branch experiences EDFA and RFA gain, while the second signal part experiences RFA gain only. These two amplified signals with the same wavelength are collected by a 2 × 1 coupler at the output side. At the output side, an optical spectrum analyzer (OSA) is used to measure the gain spectrum and NF for the amplified signal.

3 | RESULTS AND DISCUSSIONS

Figure 2 shows the amplified spontaneous emission (ASE) of the proposed PHFA amplifier in the absence of the input signal power delivered by the TLS. Generally, ASE is very important for determining the amplification band of any amplifier. Figure 2A illustrates the ASEs at the maximum pump power of 475 mW for 1410 and 1495 nm and at different 1480 nm pump powers. The 1480 nm pump power was optimized to specify the wide flatness amplification band. The results show that the 1480 nm pump power of 250 mW is the optimum power for achieving a wide

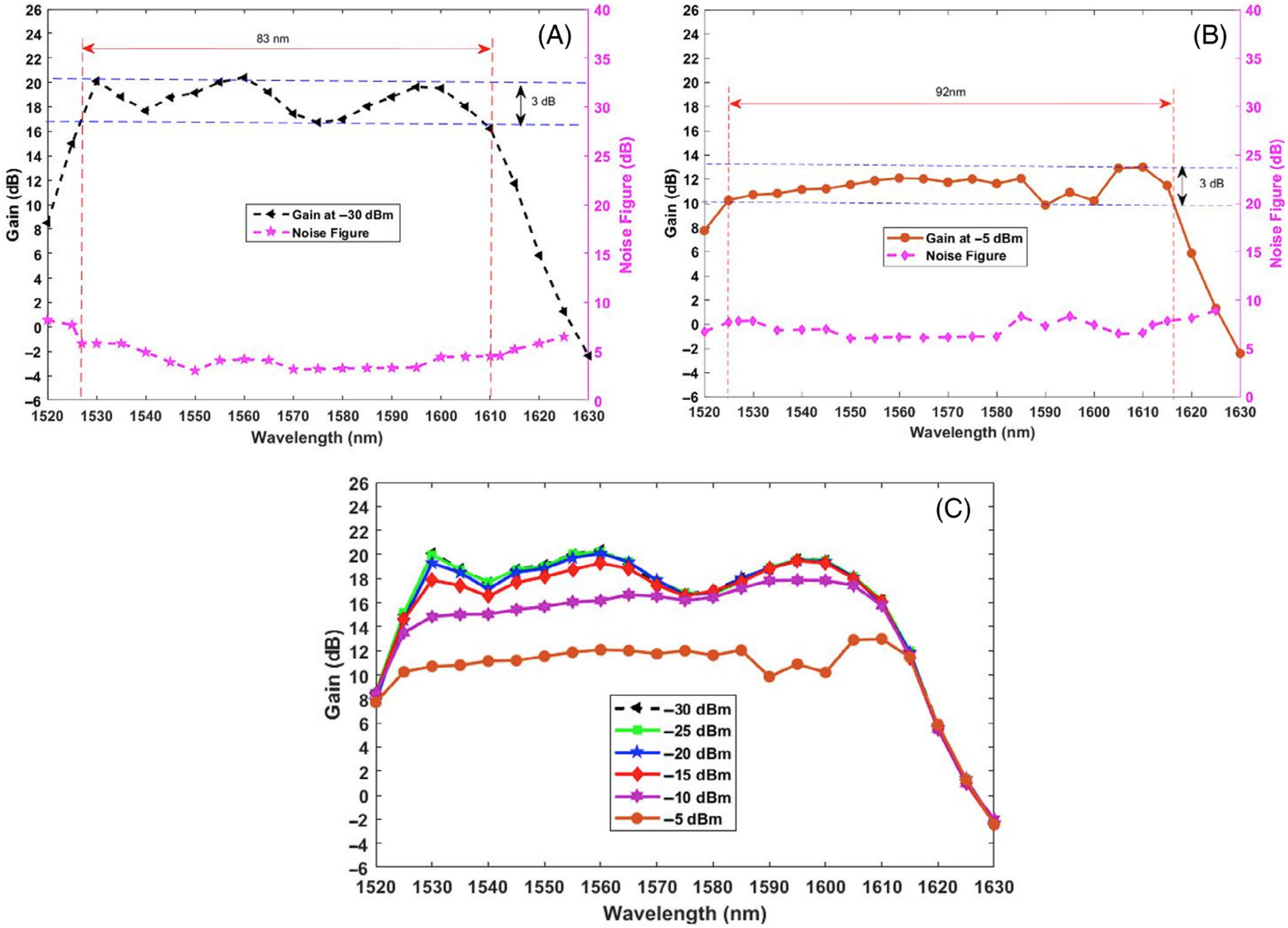

FIGURE 3 Overall gain spectrum for the proposed PHFA. (A) at low input signal power of −30 dBm, (B) at large input signal power of −5 dBm, and (C) at different input signal power from −30 to −5 dBm. PHFA, parallel hybrid fiber amplifier [Color figure can be viewed at wileyonlinelibrary.com]

amplification gain flatness. Flatness emission peak bandwidth is defined as the wavelength ranges at which the emission peak level difference should not exceed 3-dB. When the 1480 nm pump power was increased further, a high gain was observed at high pump powers of 300 and 400 mW in the C-band region in the expense of flatness gain bandwidth. In the optimization process, the maximum Raman pump power of 475 mW was used so that high Raman gain could be achieved at both of S- and L-bands regions. Generally, erbium gain is higher than the Raman gain. Therefore, an optimization in the erbium gain through the pump power variations is required to achieve wider flatness amplification emission bandwidth. Therefore, a variation in the erbium pump power that pumped by the residual of 1480 nm pump power was demonstrated and the optimal value of the pump power was 250 mW. The recorded flatness emission bandwidth at the optimal pump powers was 83 nm from 1527 to 1610 nm.

The effect of each pump power unit on the overall amplification band is presented in Figure 2B. An optimal pump powers of 475 mW for both of 1410 and 1495 nm and 250 mW for 1480 nm are utilized. Clearly, by making 1480 nm pump power off, the overall amplification band was only in the C- and L-bands in which the Raman peak gains of 1510 nm provided by the first Raman scattering related to the 1410-nm pump power in addition to the Raman peak gain at 1595 nm, which was released by the 1495-nm Raman pump unit. At the same time, the EDF will act as an absorber section as the residual pump powers from the 1410- and 1495-nm pump powers are extracted and recycled to the DCF at the first branch. By making 1410 nm pump power off, the tail gain provided at C and L-band regions was disappeared. Finally, the 1495-nm pump power only affects the Raman peak gain at 1595 nm and the support tail gain for both the 1580- and 1610-nm bands.

Figure 3 illustrates the overall gain spectrum and noise figure of the proposed parallel amplifier. The optimal pump power units were adjusted at 475 mW for 1410 and 1495 nm and 250 mW for 1480 nm. A wideband amplification of 100 nm from 1520 to 1620 nm was achieved, covering the S-, C-, and L-bands. A tunable flatness gain bandwidth of 83 nm (1527–1610 nm), which has a gain variation below 3 dB and an average gain level of 18.5 dB, was achieved for a small-signal power of −30 dBm, as shown in Figure 3A. The obtained wide flatness gain bandwidth can be attributed to the Raman amplification peaks (i.e., 1510, 1580, 1595, and 1610 nm) in addition to the EDFA peak gain (1530–1570 nm). The 1410-nm Raman pump unit generated the first-order Raman peak gain at 1510 nm and support tail gain within the entire amplification bandwidth. Meanwhile, both 1480- and 1495-nm pump units were responsible for the Raman peak gains at 1580 and 1595 nm, respectively. Under a low signal power of −30 dB, no saturation could occur. Therefore, the EDFA peak gain was optimized to achieve a wide gain flatness. The optimization was performed by optimizing the residual 1480-nm pump power inserted into the EDFA. Relatively low noise figure values of lower than 5 dB within the entire flatness gain bandwidth were recorded. In addition, the proposed amplifier was tested at a high input signal power of −5 dBm at which the overall gain saturation suffers from gain saturation, as shown in Figure 3B. A wide flatness gain bandwidth of 92 nm from 1525 to 1617 nm was recorded. At this high signal power, the EDFA was deeply saturated and led to the saturation of the RFA in the first branch because they are serially connected. Meanwhile, the RFA in the second branch showed less saturation. Figure 2B indicates that the RFA at the second amplifier stage has a lower gain level (at the 1580-nm region) than the other RFA and EDFA peak gain levels. Therefore, the high saturation in EDFA and RFA in the first branch resulted in the wide gain flatness bandwidth. More results were obtained at different input signal powers from −30 to 5 dBm with a 5-dBm step, as shown in Figure 3C. Clearly, our proposed amplifier shows a wide gain flatness within the input signal power ranges. In addition, wider flatness gain bandwidth could be achieved in higher input signal power but in the expense of gain level. Our results show a higher gain level, a wider flatness gain bandwidth, and a wider gain dynamic range than the results of previous works listed in Table 1.

The output spectrum of the amplified signal and the input signal at −30 dBm were recorded via the OSA at different wavelengths within the flatness gain bandwidth (1527–1610 nm) as shown in Figure 4. The input signal power was fixed at −30 dBm for all signal's wavelength. The output peak power and the OSNR of the amplified signals are significant, further proving the overall gain spectrum and the noise figure presented in Figure 3A for the small input signal power region. Moreover, more experimental investigations were conducted to show the gain dynamic range of the proposed PHFA. Dynamic gain range is defined as the input signal power range at which the overall gain of the amplifier can work below the saturation point in which the overall gain variation should not exceed 3 dB.

TABLE 1 The results of the previous works

Work	Results conducting type	HFA structure	Pumping technique	Optical bandwidth @ small-signal power in nm	Optical bandwidth @ large-signal power in nm	Average gain level dB
11	Simulation	PHFA	Single pump (1480 nm, 600 mW)	60 (1530–1590)	35 (1530–1565)	13.5
12	Simulation	PHFA	Single pump (1480 nm, 660 mW)	65 (1530–1595)	Not mentioned	18
13	Simulation and Experimental	Single pass PHFA	single pump (1480 nm, 800 mW)	60 (1530–1590)	60 (1530–1590)	14
14	Simulation and Experimental	Double-pass PHFA	Single pump (1480 nm, 650 mW)	60 (1530–1590)	60 (1530–1590)	22
15	Experimental	Double-pass PHFA	Multiple pump (1480 nm, 170 mW, 980 nm 170 mW)	35 nm (1525–1560)	80 nm (1525–1605)	12.1
16	Simulation	SPHFA	Multiple pump (1480 nm, 800 mW, 1495 nm, 300 mW, total pump: 1.1 W)	62.5 (1530–1592.5)	Not mentioned	13.4
17	simulation	PHFA	Multiple pump (1480 nm, 800 mW, 1495 nm, 600 mW, total pump 1.4 W)	65 (1530–1595)	45 (1550–1595)	16
18	simulation	PHFA with 32-channels	Multiple pump (1480 nm, 800 mW, 1495 nm, 600 mW, total pump: 1.4 W)	65 (1530–1595)	45 (1550–1595)	16
Our work	experimental	PHFA	Multiple pump (1480 nm, 250 mW, 1410 nm, 475 mW, 1495 nm, 475 mW, total pump 1.2 W)	83 (1527–1610)	92 (1525–1617)	18.5

Abbreviations: HFAs, Hybrid fiber amplifiers; PHFA, parallel HFA; SHFA, serial HFA; SPHFA, Single pass HFA.

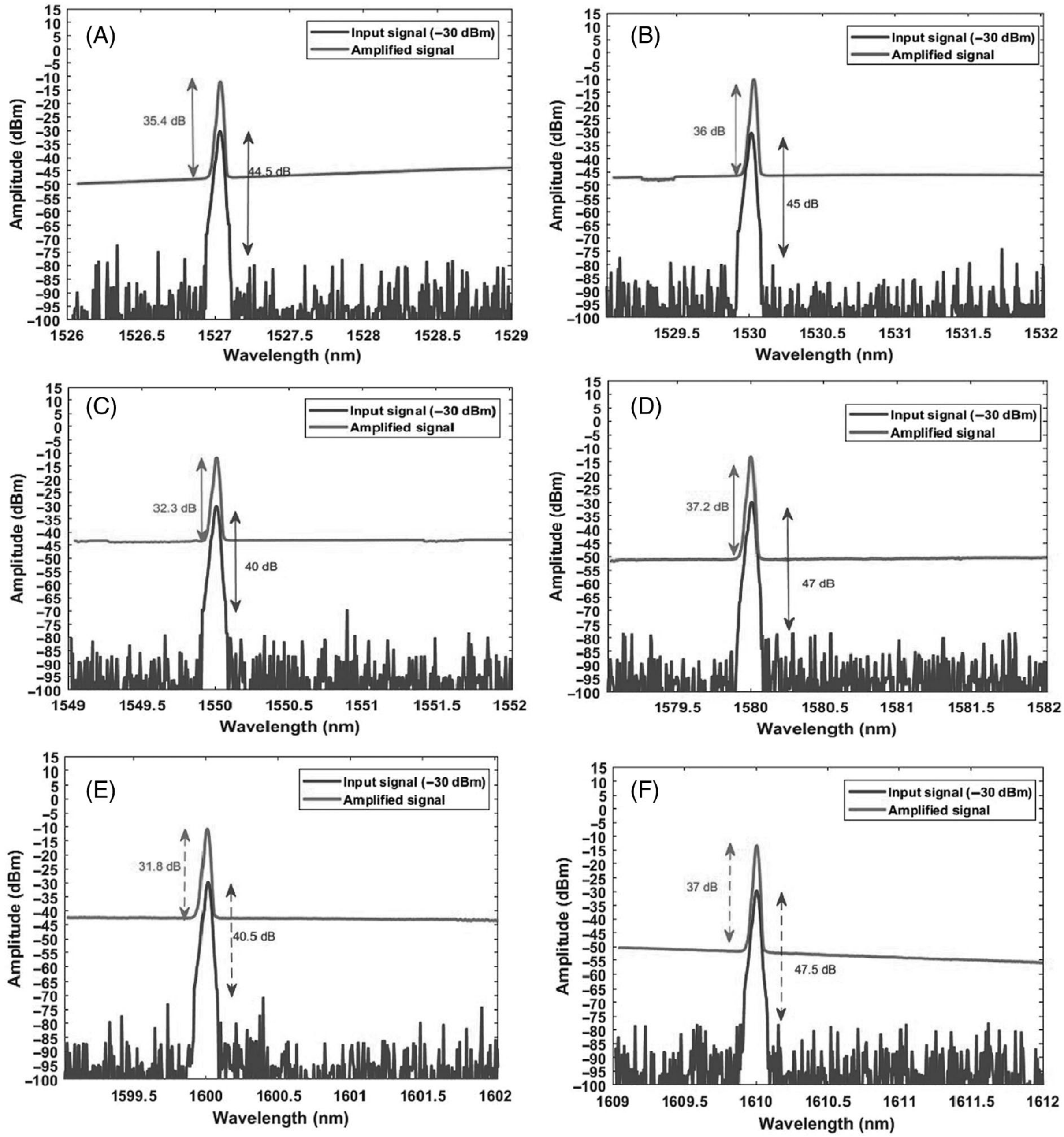

FIGURE 4 The spectrum of the input and the amplified output signal spectrum at different TLS wavelengths. TLS, tunable laser source [Color figure can be viewed at wileyonlinelibrary.com]

Figure 5 illustrates the overall gain as a function of the input signal power at different signal wavelengths within the entire gain flatness between 1527 and 1610 nm. The input power was varied from −30 to −5 dBm at 5-dBm steps. Again, the dynamic gain range was tested under different signal wavelengths to show the performance of the proposed amplifier design. Starting with 1527 nm (Figure 5A), gain saturation was observed at the input signal power of −10 dBm. In this wavelength, both Raman and erbium gains were obtained. Thus, erbium gain resulted in Raman gain saturation. Move away to 1530 nm (Figure 5B), the input saturation power was −13.5 dBm in which the erbium gain is effective. Even for the peak wavelength of the erbium at 1530 nm that should be saturated at −17 dBm, which is the normal saturation of EDFA, an additional 3 dB delay in saturation was taken due to the losses of the 3-dB coupler. Slightly away from the peak of the erbium gain to 1550 nm (Figure 5C), the gain saturation was delayed to −11 dBm. At 1580 nm (Figure 5D), for which the second RFA in the second branch is responsible, a wide gain dynamic range was obtained, and the gain was saturated at the input signal power equal to −7.5 dBm. This phenomenon is due to the 3-dB losses and the gain saturation of Raman that saturated at high input signal power compared to the erbium saturation point. Approaching 1600 nm (Figure 5E), which is very near the Raman peak gain of 1595 nm, early saturating at

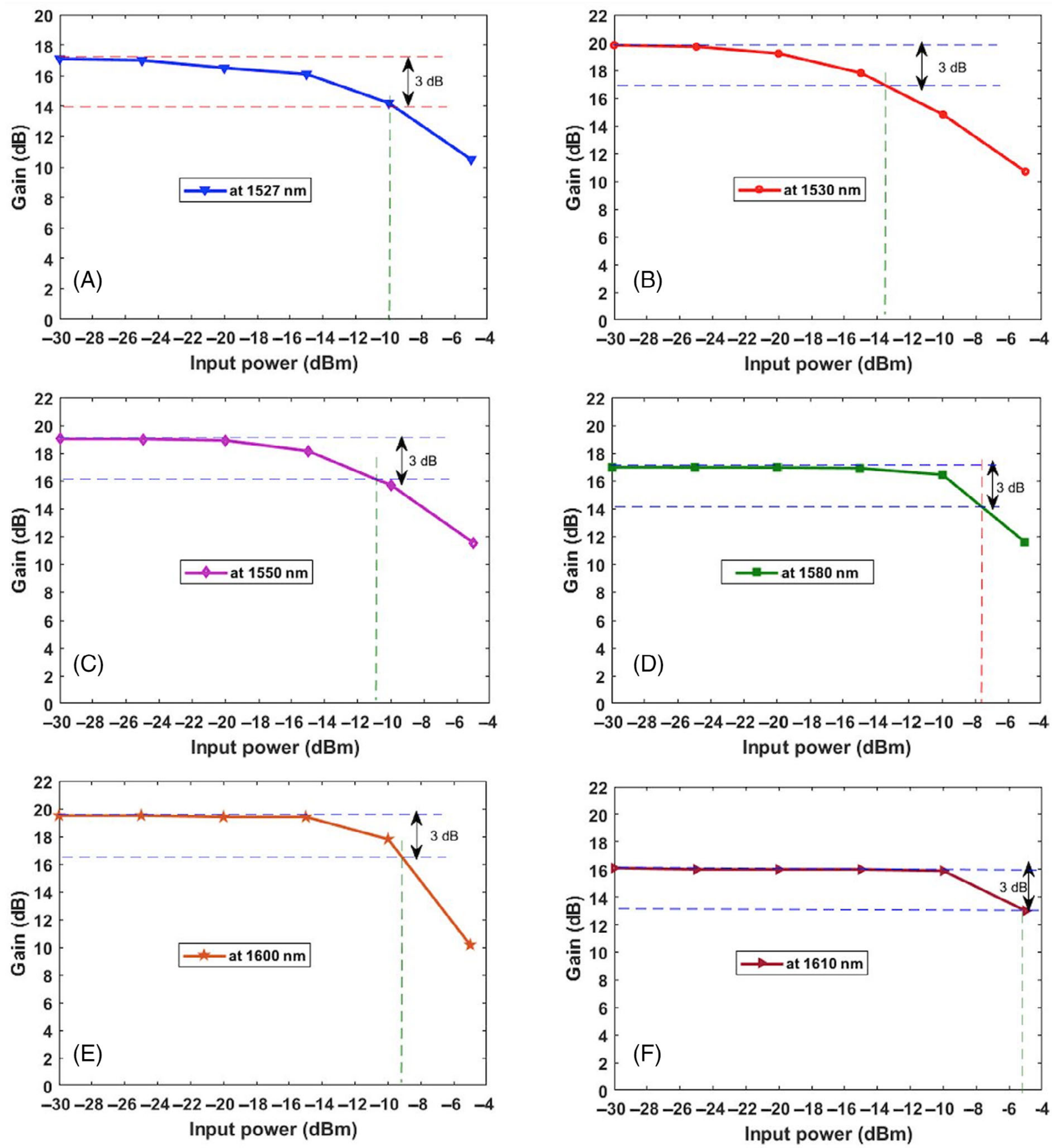

FIGURE 5 Gain dynamic range of the proposed PHFA at different TLS wavelengths. PHFA, parallel hybrid fiber amplifier; TLS, tunable laser source [Color figure can be viewed at wileyonlinelibrary.com]

−9 dBm was observed. Finally, at 1610 nm (Figure 5F), a wide dynamic gain range was recorded, and the saturation input signal power was −5 dBm. In this signal wavelength, the most effective gain is the Raman gain produced by the tail gain of 1410 nm which has a low gain level. The other gain associated is the tail of the Raman peak gain of 1595 nm. The results indicate that the gain dynamic range spectrum shows gradual saturation in the regions where erbium gain was effective until it was totally saturated (Figure 5A–C). Meanwhile, the gain dynamic range illustrates different behaviors in the input signal regions where the Raman gain was effective, and the gain saturation was nearly constant and then saturates linearly.

For performance evaluation, a detailed comparison was performed between our proposed PHFA and the previous published works. The operating type, the HFA structure, the pumping technique, and the gain flatness bandwidth at small and large input signal regions are summarized in Table 1.

4 | CONCLUSION

The performance of the proposed PHFA in terms of overall gain spectrum, noise figure, and dynamic gain range is experimentally investigated for both small and large input signal powers. Up to 83 nm (1527–1610 nm) and 92 nm

(1525–1617 nm), which cover three optical bands (S-, C-, and L-bands), were obtained as flatness gain bandwidths at small and large input signal powers of −30 and −5 dBm. This wide gain flatness was obtained by optimizing the EDFA and RFA pump power units in addition to selecting the appropriate Raman pumps units' wavelength. In addition, the Raman pump efficiency is improved by recycling the residual Raman pump power back into the Raman gain media.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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REFERENCES

[1] Agrawal GP. *Optical Amplifier Noise in Lightwave Technology*. John Wiley & Sons; 2005:185-224.
[2] Ali MH, Abdullah F, Jamaludin MZ, Al-Mansoori MH, Al-Mashhadani TF, Abass AK. Effect of EDF position on the performance of hybrid dispersion-compensating Raman/EDF amplifier. *Fourth International Conference on Photonics (ICP 2013)*. IEEE; 2013.
[3] Ali MH, Abdullah F, Jamaludin MZ, Al-Mansoori MH, Abass AK, Al-Mashhadani TF. Effect of cascading amplification stages on the performance of serial hybrid fiber amplifier. *Fiber Integr Opt*. 2015;34(3):157-170.
[4] Abdullah F, Jamaludin MZ, Ali MH, Al-Mansoori MH, Abass AK, Al-Mashhadani TF. Influence of Raman pump direction on the performance of serial hybrid fiber amplifier in C+L-band. *Seventh International Conference on Photonics (ICP 2018)*. IEEE; 2018.
[5] Kumar C, Goyal R. Performance analysis of hybrid optical amplifiers for super dense wavelength division multiplexing system in the scenario of reduced channel spacing. *MAPAN-J*. 2017;33:159-164.
[6] Masuda H, Kawai S, Aida K. 76-nm 3-dB gain-band hybrid fiber amplifier without gain-equalizer. *Opt Amplifiers Appl*. 1998;25:78-81.
[7] Seo HS, Ahn JT, Park BJ, Chung WJ. Double-pass resonant Er-Raman amplifier. *Electron Lett*. 2007;43(15):801-802.
[8] Liaw SK, Huang YS. C+L-band bybrid amplifier using FBGs for dispersion compensation and power equalisation. *Electron Lett*. 2008;44(14):3-4.
[9] Almukhtar AA, al-Azzawi AA, Ahmad BA, et al. Flat-gain and wide-band partial double-pass erbium co-doped fiber amplifier with hybrid gain medium. *Opt Fiber Technol*. 2019;52:101952.
[10] Almukhtar AA, al-Azzawi AA, Cheng XS, et al. Enhanced triple-pass hybrid erbium doped fiber amplifier using distribution pumping scheme in a dual-stage configuration. *Optik (Stuttg)*. 2020;204:164191.
[11] Liaw SK, Huang CK, Hsiao YL. Parallel-type C+L band hybrid amplifier pumped by 1480 nm laser diodes. *Laser Phys Lett*. 2008;5(7):543-546.
[12] Liaw SK, Dou L, Xu A, Huang YS. Optimally gain-flattened and dispersion-managed C+L-band hybrid amplifier using a single-wavelength pump laser. *Opt Commun*. 2009;282(20):4087-4090.
[13] Ali MH, Abdullah F, Jamaludin MZ, Al-Mansoori MH, Al-Mashhadani TF, Abass AK. Simulation and experimental validation of gain-control parallel hybrid fiber amplifier. *J Opt Soc Korea*. 2014;18(6):657-662.
[14] Ali MH, Abdullah F, Al-Mashhadani TF. Gain-control technique in double-pass parallel hybrid fiber amplifier. *Opt Quantum Electron*. 2020;52(9):1-7.
[15] Al-Azzawi AA, Almukhtar AA, Reddy PH, et al. An efficient wideband hafnia-bismuth erbium co-doped fiber amplifier with flat-gain over 80 nm wavelength span. *Opt Fiber Technol*. 2019;48:186-193.
[16] Abass AK, Ali MH, Al-Hussein SAA. Wideband flat–gain hybrid fiber amplifier utilizing combined serial–parallel configuration. *Int J Nanoelectron Mater*. 2018;11(Special Issue BOND21):17-22.
[17] Abass AK, Ali MH, Al-Hussein SAA. Optimization of hybrid fiber amplifier utilizing combined serial-parallel configuration. *IOP Conf Ser Mater Sci Eng*. 2018;454:12014.
[18] Ali MH, Abass AK, Abd Al-Hussein SA. 32 channel × 40 Gb/s WDM optical communication system utilizing different configurations of hybrid fiber amplifier. *Opt Quantum Electron*. 2019;51(6):188.

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