Optimization of Hybrid Fiber Amplifier Utilizing Combined Serial-Parallel Configuration

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Abstract. In this paper, the optimum pump conditions are determined for C+L band combined serial-parallel hybrid fiber amplifier (CSP-HFA), utilizing gain control technique via OptiSystem 7.0. The optimization includes determining the optimum pump power (OPP), the optimum pump wavelength (OPW) and optimum coupling ratio (OCR), within the longest 3–dB flat gain bandwidth. The proposed HFA at optimum conditions, produced 65 nm flat gain bandwidth ranging from 1530 nm to 1595 nm within average gain of 16 dB and average NF of 7.29 dB. The proposed architecture provided two advantages over the conventional P-HFA includes; 1) improved flat gain bandwidth by 8.33 %, 2) constant optimum coupling ratio for both small and large signal at 0.7.

Keywords: Serial-parallel hybrid fiber amplifier, optimum pump condition, flat gain bandwidth.

1. Introduction
Optical amplifiers are irreplaceable optical devices used to compensate fiber losses long-haul transmission systems [1–3]. The hybrid Raman/EDFA is a promising technology for future dense wavelength division multiplexing (DWDM) systems [4]. The design of Hybrid Raman/erbium-doped fiber amplifier was used for many purposes such as maximizing the span length and improving the bandwidth of EDFA [5]. The fiber amplifier is a fiber laser but with the absence of positive feedback, and it can be classified into two categories, linear fiber amplifier (rare earth-doped fiber amplifiers) and nonlinear fiber amplifier (Raman fiber amplifier and Brillouin fiber amplifier). The most popular linear fiber amplifier is the EDFA since it covered the whole conventional communication band (C-band) [6].

In this context, the HFA based on the input signal path can be divided into two types, namely, serial and parallel hybrid fiber amplifiers [7]. Generally the serial design characterized by high gain level and acceptable noise figure, but the narrow gain bandwidth is considered as a main drawback when it is used with DWDM system. Therefore, different configurations and several techniques were proposed in order to address the gain flatness problem. Masuda et. al. in 1998 and S. K. Liaw et. al. in 2008, produced 76 nm and 65 nm flat gain bandwidth, respectively [6, 7], but, they used complex designs and costly components. Furthermore, S. K. Liaw et. al. in 2008 achieved 65 nm flat gain bandwidth in C+L band utilizing simple parallel configuration. The gain spectra are flattened by optimally dividing the pump power ratio to 1:29 for EDFA and RFA, respectively [10]. However, the system suffers from
degradation about 4 dB and 6 dB in gain flatness at the large signal region of -10 dBm and 0 dBm, respectively.

In our previous work [7] we proposed the gain control technique in order to improve the gain bandwidth of P-HFA by optimally dividing the signal power. Wide flat gain bandwidth over a range of 60 nm from 1530 nm to 1590 nm was achieved at the signal power range from -30 dBm to -5 dBm with optimum coupling ratios 0.4 and 0.8, respectively. However, this system have two main drawbacks, namely, the dispersion compensation in EDFA branch and there are two optimum coupling ratio 0.4 for small signal and 0.8 for large signal.

In this paper, we solved the dispersion problem in [7] by inserting a 7 km DCF (RFA1) and determining its OPP and OPW at 600 mw and 1495 nm, respectively. As a result, a new HFA is presented based on the combination between serial (EDFA+RFA1) and parallel with (RFA2). The proposed architecture provided two advantages over the design in [7] includes; 1) improved flat gain bandwidth by 8.33 %, 2) constant optimum coupling ratio for both small and large signal at 0.7.

2. Simulation Model

The simulation model of the proposed CSP–HFA is illustrated in Figure 1. A variable optical coupler is used to control the input signal power between the two branches (EDFA/RFA1 and RFA2). The input signal is provided by a tunable laser source (TLS) with maximum power 10 dBm, wavelength ranging from 1530 nm to 1595 nm and linewidth of 150 kHz. The EDFA is a 3 m length of EDF pumped by residual Raman pump power at 1480 nm. A variable optical attenuator (VOA) is used to control the EDFA pump power. The Er$^{3+}$ ion concentration is 440 ppm, core radius is 1.65 µm, Er doping radius is 1.65 µm, and cut–off wavelength is 1300 nm. The gain medium for both of the RFA1 and RFA2 is 7 km DCF pumped by Raman pump unit (RPU) in counter pump configuration. The OPP for the RFA2 and EDFA is about 800 mW and 100 mW, respectively. While the OPP and OPW for RFA1 is determined in this work to compensate the dispersion and enhance the overall system performance.

Several pump wavelengths are investigated in this work, namely, 1480 nm, 1485 nm, 1490 nm and 1495 nm, as well as the pump power is varied from 200 mW to 700 mW with a step of 100 mW. The DCF has total loss of 4.4 dB, effective area of 20 µm$^2$, a nonlinear coefficient of $14.5 \times 10^{-10}$ W$^{-1}$ and dispersion parameter of $-110$ ps/nm/km. A wavelength selective coupler (WSC) is used to capture the residual Raman pump and re-inserted into the EDF. An optical fiber coupler (OFC) is used to collect the output signal from the two branches. Finally, optical spectrum analyzer (OSA) is used, to record the total system gain and NF.

Figure 1. Schematic diagram of CSP–HFA utilizing gain controlled technique.
3. Results and Discussion
The optimization of the proposed design is divided into three categories, pump power optimization, pump wavelength optimization and coupling ration optimization.

3.1. Pump power optimization
In this part, the RPP of the CSP–HFA has been optimized in order to obtain maximum $G_{av}$ as well as wide 3–dB gain flatness and acceptable NF. The input signal power is fixed at $-20$ dBm, while the wavelength is tuned from 1530 nm to 1595 nm with a step of 5 nm. The coupling ratio ($n$) is set at 0.5 which represents the ratio of a conventional 3–dB optical coupler. The RPP is swept from 200 mW to 700 mW with a step of 100 mW for pumping wavelengths of 1480 nm, 1485 nm, 1490 nm, and 1495 nm simultaneously, as shown in Figure 2 (a), (b), (c) and (d), respectively.

The analyzed data from Figures 2 show the main parameters are taken into account through the pump power optimization is depicted in Table 1. According to the results, at a pumping wavelength of 1480 nm, higher 3–dB gain flatness about 45 nm was observed at RPP of 200 mW and 300 mw. While, the $G_{av}$ and $NF_{av}$ were better at RPP of 300 mW as compared with 200 mW. In addition, for the pump wavelengths of 1485, 1490 and 1495 nm, the higher 3–dB gain flatness, higher average gain and lower $NF_{av}$ were observed at 600 mw pump power rendering it as the OPP for these wavelengths.
Figure 2. Net gain and NF versus signal wavelength for CSP–HFA within $n = 0.5$. The signal power is fixed at $-20$ dBm and pump power is changed from 200 mw to 600 mw with a step of 100 mW, for the pump wavelength of: (a) 1480 nm, (b) 1485 nm, (c) 1490 nm and (d) 1495 nm.
Table 1. The main parameters which taken into account through the pump power optimization for RFA1.

| RPP | $G_{av}$ (dB) | $G_{var}$ (dB) | $NF_{av}$ (dB) | 3–dB $GBW$ (nm) |
|-----|---------------|---------------|---------------|----------------|
| 200 | 13.39         | 1.92          | 8.36          | 45             |
| 300 | **14.34**     | **2.3**       | **8.23**      | **45**         |
| 400 | 15.66         | 1.99          | 8.01          | 40             |
| 500 | 16.93         | 2.45          | 7.90          | 40             |
| 600 | 18.33         | 2.93          | 7.79          | 40             |
| $\lambda_p = 1485$ nm | 200 | 13.21         | 1.98          | 8.38          | 45             |
|     | 300 | 14.05         | 1.99          | 8.24          | 45             |
|     | 400 | 15.02         | 1.96          | 8.17          | 45             |
|     | 500 | 16.31         | 2.54          | 8.05          | 45             |
|     | **600** | **17.36**     | **2.75**      | **7.93**      | **45**         |
| $\lambda_p = 1490$ nm | 200 | 13.03         | 2.15          | 8.41          | 45             |
|     | 300 | 13.75         | 1.81          | 8.28          | 45             |
|     | 400 | 14.59         | 1.97          | 8.17          | 45             |
|     | 500 | 15.54         | 2.18          | 8.09          | 45             |
|     | **600** | **16.61**     | **2.55**      | **7.97**      | **45**         |
| $\lambda_p = 1495$ nm | 200 | 12.89         | 2.21          | 8.43          | 45             |
|     | 300 | 13.50         | 1.89          | 8.32          | 45             |
|     | 400 | 14.21         | 1.75          | 8.21          | 45             |
|     | 500 | 15.01         | 1.66          | 8.13          | 45             |
|     | **600** | **15.92**     | **2.09**      | **8.03**      | **45**         |

3.2. **Pump wavelength optimization**

In order to determine the OPW for the RFA1, both of the gain profile and NF at the OPP for several pump wavelengths were compared as illustrated in Figure 3 (a) and (b), respectively. According to the results, the average gain increased as the pump wavelength increased from 1480 nm to 1490 nm, then start to degrade at pump wavelength of 1495 nm. This is due to the fact that the gain spectrum of the RFA1 is shifted away from the gain spectrum of the PHFA.

In addition, for more careful investigation of the gain profile behavior for the proposed design at different RFA1 pump wavelengths, the analyzed data from Figure 3 shows the main parameters that have taken into account through the pump wavelength optimization which is depicted in Table 2. From the results, the 3–dB GBW is about 45 nm as well as there is no distinguished difference in $G_{av}$, $G_{var}$, and $NF_{av}$ for all selected pump wavelengths at OPP, so it is difficult to select the OPW from these results. In the next section, another optimization method is required, namely, OCR, in order to determine the OPW and investigate signal coupling ratio impact on the gain profile of the proposed design at different pump wavelengths as well as select the OCR.
Figure 3. (a) Gain characteristics and (b) NF of CSP–HFA versus signal wavelength within CR of 0.5, at several RFA1 pump wavelengths at OPP for signal power of –20 dBm.

Table 2. The analyzed data from Figure 3 showing the main parameters which taken into account through the pump wavelength optimization for RFA1.

| RPW(nm) at OPP | $G_{av}$, dB | $G_{var}$, dB | NF$_{av}$, dB | 3–dB $G_{BW}$, (nm) |
|---------------|--------------|---------------|---------------|------------------|
| 1480 (OPP = 300 mw) | 14.34 | 2.3 | 8.22 | 45 |
| 1485 (OPP = 600 mw) | 17.32 | 2.75 | 7.89 | 45 |
| 1490 (OPP = 600 mw) | 16.60 | 2.55 | 7.97 | 45 |
| 1495 (OPP = 600 mw) | 15.92 | 2.09 | 8.03 | 45 |

3.3. Coupling ratio optimization

In order to determine the OPW as well as OCR for the proposed amplifier, the 3–dB flat $G_{BW}$, versus signal coupling ratio of different RFA1 pump wavelength is investigated as depicted in Figure 4. In this part, the flat $G_{BW}$, is investigated at OPP and different signal CR for n = 0.2 to 0.8 for all selected pump wavelengths. The results show that the change in CR has insignificant effect on the gain bandwidth at pump wavelength of 1480 nm, 1485 nm and 1490 nm as well as the 3–dB flat band is approximately 45 nm. While, for the pump wavelength of 1495 nm, the results show that the change in CR has a significant effect on the gain bandwidth and the flat $G_{BW}$, is about 65 nm from 1530 nm to 1595 nm at n = 0.7.
Figure 4. 3-dB flat gain bandwidth versus coupling ratio for several RFA1 pump wavelengths of 1480nm, 1485nm, 1490nm and 1495nm.

From the foregoing, the OPW and OCR are 1495 nm and 0.7, so the gain profile at optimum conditions for small and large signal region is investigated as illustrated in Figure 5 (a) and (b), respectively. In this work, (n) is varied from 0.2 to 0.8; the pump power is fixed at OPP of 100 mW, 600 mW and 800 mW for EDFA, RFA1 and RFA2, respectively. The signal wavelength is varied from 1530 nm to 1595 nm step 5 nm.

The overall gain spectra can be divided into two regions; C–band region extended from 1530 nm to 1565 nm, where EDFA is more effective, L–band region extended from 1565 nm to 1595 nm, in which the RFA is more efficient. In addition, the results show that the CR is more effective in the C–band region. The proposed amplifier shows best performance at n = 0.7 within $G_{av} = 16$ dB, $NF_{av} = 7.29$, 3–dB bandwidth of 65 nm at small signal region. Although, the 3–dB band is degrade to 45 nm at large signal of $–5$ dBm, but the OCR is still constant at n = 0.7.
4. Conclusion
The gain profile and the NF for CSP-HFA utilizing gain control technique is investigated via OptiSystem 7. In addition, the optimum pump conditions as well as the optimum signal coupling ratio for the RFA in serial branch is determined. The 3-dB gain bandwidth is improved by 44.44 % by optimizing the CR from a conventional value of 0.5 to the optimum value at 0.7, within average gain and NF of 16 dB and 7.29 dB, respectively. Furthermore, proposed design can compensate the chromatic dispersion for a transmission span of 44 km for both amplifier branches.

5. References
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