Influence of Raman Pump Direction on the Performance of Serial Hybrid Fiber Amplifier in C+L-Band

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***Abstract*—This study demonstrates the simulation and experimental validation of a serial hybrid Raman/erbium-doped fiber amplifier in the C+L optical communication bands. The erbium-doped fiber is pumped by the residual Raman pump to enhance pump conversion efficiency in forward (Type A) and backward (Type B) direction. The amplifier was tested with three different input levels where the overall finding shows Type B provides better gain (average of 20dB across band) than Type A at the expense of noise figure (2dB higher).**

***Index Terms*—serial hybrid fiber amplifier, conventional technique, recycling technique**

I. Introduction

Optical amplifiers is an essential element in long-haul transmission system to compensate for fiber loss [1]. Two popular types of optical amplifier studied by many researchers are erbium-doped fiber amplifier (EDFA) and Raman fiber amplifier (RFA) [2], [3]. EDFA is mainly used for conventional communication window (C-band) from 1530 nm to 1570 nm. When dense wavelength division multiplexing (DWDM) move to L-band, increasing the EDF length is employed as a quick solution so that EDFA can be used within the band. However, this approach requires high pump power but provides lower gain with higher NF [4]. RFA on the other hand can provide gain at any wavelength within the transparency window of optical fiber by simply changing the pump wavelength [1]. However, its limitations is in terms of gain level, flatness and pump conversion efficiency [5]. Therefore, the logical way forward it to combine EDFA and RFA to create hybrid fiber amplifier (HFA).

In recent years, HFA attracted huge attention as an enabling and promising technology for future DWDM multi-terabit systems [6]–[8] due to longer span length, reduced nonlinearities, larger gain bandwidth and enhanced gain flatness [5]. There are two typical design of hybrid fiber amplifiers; serial (S-HFA) [9] and parallel (P-HFA) [10]. In S-HFA, the input signal has two stages of amplification where first stage output is used as an input signal to second stage, in a single pass. RFA is usually designed with counter-pumping to minimize the effects of pump-to-signal relative-intensity noise transfer [1]. However, with lower noise pump lasers, the co-pumping and bidirectional pumping schemes are realized in distributed RFA [11], discrete RFA [12] and also in EDFA [13].

In this paper, the effect of the Raman pump direction on S-HFA is simulated and experimentally validated. Two different schemes are adopted; Type A (co-pumping) and Type B (counter-pumping). The EDFA is counter-pumped by the residual Raman pump in both configurations.

II. Simulation Setup

Two SHFA illustrated in Figure 1 were simulated utilizing Optisystem-10 and experimentally validated. A tunable laser source (TLS) with power varying from -30 dBm to 0 dBm and wavelengths varying from 1530 nm to 1600 nm is used as input source. The RFA is constructed using 7 km dispersion compensating fiber (DCF) pumped by a Raman pump unit (RPU) at 1480 nm. The DCF has total loss, effective area, nonlinear coefficient and dispersion parameter of 4.4 dB, 18.5 μm^2, 14.5$\times 10^{-10} W^{-1}$ and -110 ps/nm/km, respectively. The fiber can compensate for the accumulated dispersion in approximately 46.66 km of standard single mode fiber.

The EDFA was created using 3 m long erbium doped fiber (EDF) and pumped by the residual Raman pump power which is controlled by a variable optical attenuator (VOA). The Er^{3+} ion concentration, core radius, and cutoff wavelength of EDF are 440 ppm, 1.9μm, and 1300 nm, respectively. A wavelength selective coupler (WSC) is used to separate the residual Raman pump from the reflected Rayleigh scattering signal. The output spectrum were recorded using Optical Spectrum Analyzer, OSA1 for hybrid output signal (RFA+EDFA) and RFA output signal while OSA2 was recording EDFA output signal.

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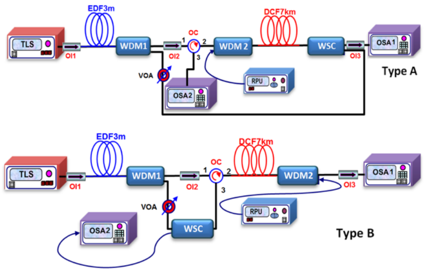

Fig. 1. Simulation setup of the serial hybrid fiber amplifier

III. Results and Discussion

The hybrid gain profile for both configurations at different input signal powers (Pin) is depicted in Figure 2. The Raman pump power (RPP) and erbium pump power (EPP) are set to 600 mW and 50 mW, respectively. At small input (-30 dBm), both configurations have a similar gain profile where average gain level is 22.7 dB and the 3-dB gain bandwidth is 40 nm (1543 nm to 1583 nm), covering both C- and L-band. At this moment, both RFA and EDFA provide amplification. At medium input (-15 dBm), the amplification bandwidth improved to 45 nm for both configurations, but the average gain level decreased to 20.2 dB and 21.5 dB for Type A and B, respectively.

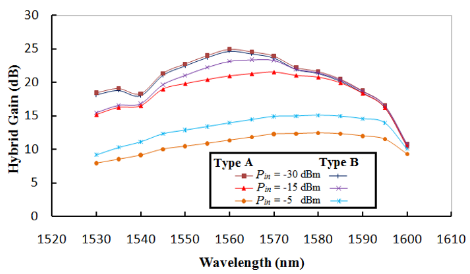

Fig. 2. Effect of the input signal power on the hybrid gain profile

Furthermore, at large input (-5 dBm), Type A exhibit lower average gain and higher 3-dB gain bandwidth compared to Type B. The average gain is about 11.2 dB (60nm bandwidth) and 14.1 dB (50nm bandwidth), for Type A and B, respectively. This is because the gain saturated faster in co-pumping scheme than in the counter-pumping due to Brillouin scattering effect. For Type A, both the signal and the pump were combined at the same end of RFA, which leads to an effective amplification while for Type B, they were attenuated before combination. Because of that, in Type A, the signal surpases stimulated Brillouin scattering (SBS) threshold faster which leads to earlier gain saturation earlier [14], [15].

Figure 3(a) and 3(b) illustrates the gain spectrum of S-HFA, RFA and EDFA at two input wavelength, 1560 nm and 1580 nm. At small signal, both types provide similar gain where at 1560 nm, EDFA provided more gain than RFA and at 1580 nm, it the opposite. This is expected since the EDF is used to provide more gain in the C-band range. As the input power increases, the gain started to saturate. The gain provided by EDFA is the same for both types due to the fact that it is pumped by the same residual Raman. However, Type A saturates faster at both wavelength due to SBS generation in the Raman gain media.

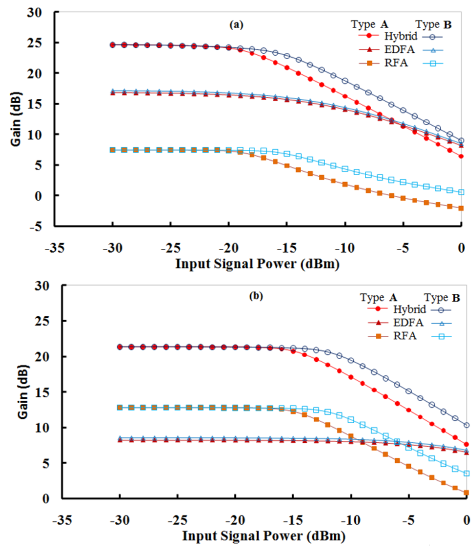

Fig. 3. Gain level vs. input signal power at two different wavelengths (a) 1560 nm and (b) 1580 nm

The influence of pump location to the noise figure (NF) is demonstrated in Figure 4. At small input, both types show almost similar value between 5 to 6 dB accross C+L-band. However, at large input, Type A suffers higher NF (7.72dB) compared to Type B (5.92 dB) due to earlier gain saturation.

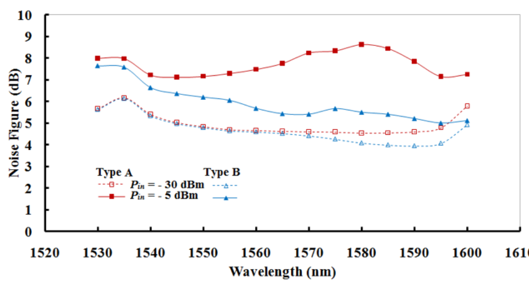

Fig. 4. Noise figure vs. wavelength for both types at the input signals of -30 dBm and -5 dBm

The S-HFA was validated experimentally using same parameters from the simulation. Fig. 5(a) and 5(b) illustrate the gain and noise figure at small and large input power for Type A and B, respectively. The result from experiment shows almost perfect agreement with the simulated model.

IV. Conclusion

The influence of Raman pump direction on the SHFA performance was simulated and experimentally validated. The effect of pump direction on the performance of the hybrid fiber amplifier is insignificant for a small input signal. However,

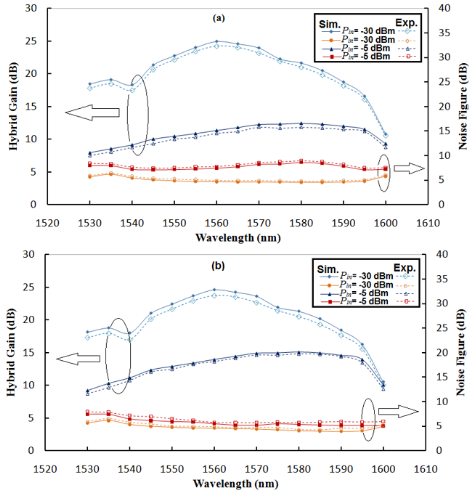

Fig. 5. Gain spectra and NF at the input signals of -30 dBm and -5 dBm for (a) Type A and (b) Type B

at large input signal, Type B shows better performance as compared to Type A where it has wider gain dynamic range, higher gain saturation power and lower average noise figure. This differences can be attributed to the fact that in Type A, saturation happens faster due to stimulated Brillouin scattering in the Raman gain media.

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