Experimental Demonstration of Raman-Assisted Phase Sensitive Amplifier with Reduced ASE Noise Level and More than 25dB Net Gain

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Abstract: The performance of a black-box Raman-assisted PSA amplifier is experimentally evaluated. In a 20-Gbaud QPSK system, more than 25dB net gain is demonstrated. Comparing to a 4dB-noise-figure EDFA, ~1.5dB ASE noise level reduction is observed.

OCIS codes: (290.5910) Scattering, stimulated Raman; (060.4370) Nonlinear optics, fibers.

1. Introduction

Phase sensitive amplifier (PSA) has gotten a lot of attention as a key device for the next generation optical communication systems [1,2]. Better noise performance than other amplification techniques like EDFA, have been verified with various architectures experimentally using nonlinear media such as highly nonlinear fiber (HNLF), and Periodically Poled Lithium Niobate (PPLN) [3-5]. Those PSAs still have some differences in amplifier operation from EDFA. Reported PSAs require precise dispersion compensation on transmission line and active pump phase control with kHz order [1] due to separation of idler generation stage and phase sensitive amplification stage located before and after transmission fibers.

We have introduced Raman amplifier stage between the idler generation stage and the PSA stage [6,7], which preferably amplifies PSA-pump and idlers with placing signal off the Raman gain bandwidth to compensate signal and idler power imbalance as well as boost up PSA pump to avoid active pump control [8]. However, it might be valuable to consider all the stages in PSA as a single black box amplifier unit and make a comparison to an EDFA.

In this paper, we experimentally demonstrate a black-box Raman-assisted PSA amplifier with ~6dB total insertion loss including ~2dB idler generation loss. This black-box amplifier gives more than 25dB net gain on a 20G-baud QPSK signal. By comparing the amplifier to a commercial benchtop EDFA with 4dB noise figure (NF), ~1.5dB ASE noise floor reduction is observed.

2. Concept

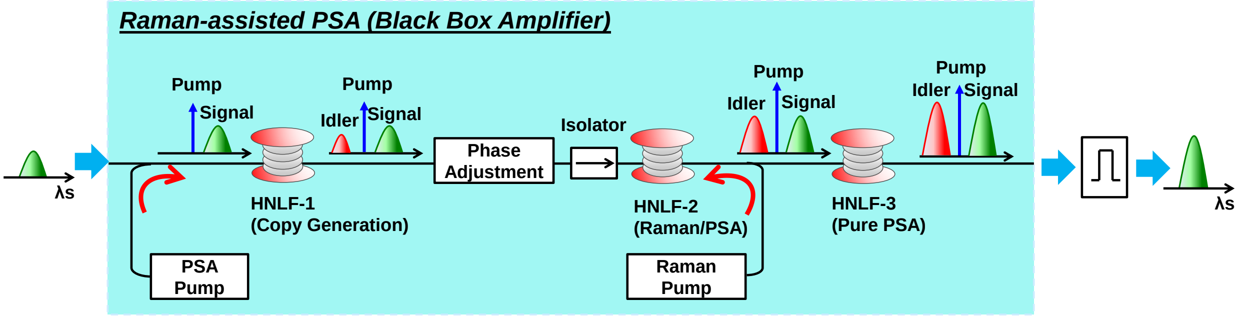

Fig. 1. Concept of the in-line Raman-assisted PSA as a black box amplifier.

Figure 1 shows the concept of the in-line Raman-assisted PSA as a black box amplifier. After long distance transmission, the signal suffers a high link loss. In the PSA black box amplifier, the signal is first coupled with a PSA pump in a HNLF, where a copy channel (idler) is generated. In order to suppress the noise on the signal wavelength at the idler generation stage, the PSA pump power is adjusted to have moderate conversion efficiency (~ -10dB). Afterwards, a low loss phase shifter is included for potential phase adjustment where fiber Bragg grating (FBG) might be an option. For optimal PSA performance, equal power of the signal and idler is preferred, which can be achieved by sending them into a hybrid Raman/PSA stage with uneven Raman gain. In this stage, the higher gain on the idler offsets the power imbalance between the signal and the idler. Meanwhile, the PSA pump is also boosted by Raman amplification in the same path and as a result, phase lock loop (PLL) is not required in this system. After that, the stage of pure PSA boosts the system net gain and could also help to optimize the ASE noise level. Finally, the amplified signal is filtered out and sent either to the receiver or to the next transmission link.

3. Experimental Setup

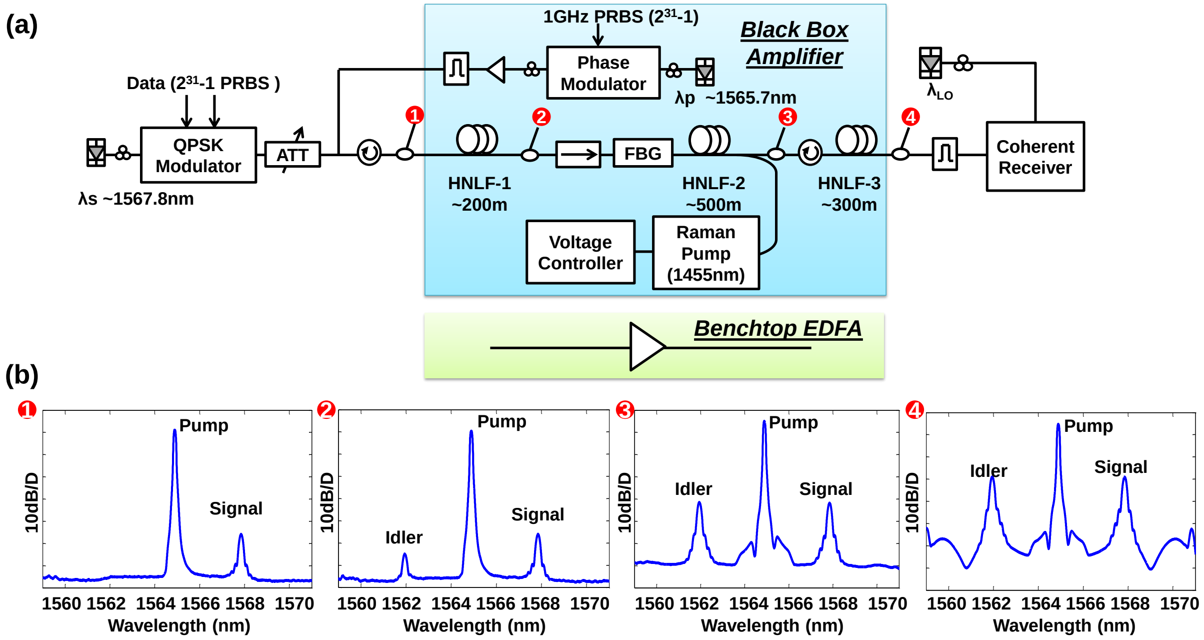

Fig. 2. (a) Experimental setup for in-line Raman-assisted PSA, whose performance is evaluated as a black box amplifier and compared to a commercial benchtop EDFA with noise figure of ~4dB; (b) measured spectra at the corresponding nodes with observed gain of more than 25 dB between node-1 and node-4. All vertical axes have the same level.

Figure 2(a) illustrates the experimental setup for the Raman-assisted PSA, where all the components in the box are treated as a black box amplifier. The total insertion loss of the black box amplifier is ~6dB including ~2dB idler generation loss. It is noted that the performance might be improved further by optimizing the insertion loss especially in idler generation stage. In the transmitter, a 20-Gbaud QPSK data modulates a laser at the wavelength of ~1567.8nm. Then, an attenuator is added to emulate the optical link loss. Afterwards, the attenuated QPSK signal is coupled with a 21dBm PSA pump, which is phase modulated with a 1GHz pseudorandom-binary-sequence (PRBS) for stimulated Brillouin scattering (SBS) suppression. The spectrum before sending to the black box amplifier is shown in Fig. 2(b1). The three HNLFs in the black box amplifier have similar parameters with nonlinear coefficient of 21.4 $W^{-1}km^{-1}$, zero dispersion wavelength (ZDW) of 1551.5nm and a dispersion slope of 0.043ps/km/nm^2 [9]. After 200m HNLF-1, an idler is generated with -9dB conversion efficiency which is shown in Fig. 2(b2). Because of the low pump power, there is no optical parametric amplification (OPA) gain on the signal. Then, a low loss (0.4dB) fiber Bragg grating with less-than-1nm reflection bandwidth is added for the potential phase adjustment. Since the pump wavelength (~1565.7nm) is close to the FBG center wavelength (~1566.3nm), only the phase of pump can be changed while the signal and idler remain unaffected.

In the next stage, the signal, idler and the pump are all boosted by Raman amplification in 500m HNLF-2. Since the signal is located at the edge of the Raman gain profile, smaller gain is observed on the signal compared to the idler. The uneven gain and simultaneous PSA erase the -9dB power imbalance between signal and idler as shown in Fig. 2(b3). Comparing to the original input signal as in Fig. 2(b1), the net gain in Fig. 2(b3) is ~14dB. In the following, a pure PSA stage with 300m HNLF-3 gives the gain boosting of another ~12dB as shown in Fig. 2(b4). Therefore, the output signal has ~26dB net gain. In the end, the signal is filtered out and sent to the receiver. The periodic peaks and dips in Fig. 2(b4) might be caused by single-mode-fiber (SMF) pigtail and it could be potentially removed by direct splicing.

A commercial benchtop EDFA with ~4dB NF is used for comparison with the black box amplifier as shown in Fig. 2(a). During comparison, both input and output signal power are ensured to be the same. Therefore, the performance is compared under the same net gain on the signal.

4. Results and Discussions

The system performance is first assessed by tuning the power of Raman pump and PSA pump as shown in Fig. 3. It is noted that the lower Raman voltage corresponds to higher Raman pump power. In Fig. 3(a), when PSA pump is fixed at 21dBm, with deceasing Raman voltage, the system net gain can reach above 25dB. When the Raman voltage is above 14V, the Raman pump power is too small to give amplification and the resultant net gain is -5dB. Considering ~6dB insertion loss of the system, PSA pump alone can only give ~1dB OPA gain on the signal after three spools of HNLF with total length of 1km. The reason might be attributed to the relative low PSA pump power and the fact that the wavelength is ~15nm away from ZDW of 1551.5nm in the HNLFs.

With fixed Raman pump voltage of 10V, increasing the PSA pump power also increases system net gain which can even reach above 30dB. However, the high power PSA pump could also bring extra nonlinear distortion to the amplified signal and 21dBm PSA pump power is selected based on the monitoring of signal's EVM at the receiver.

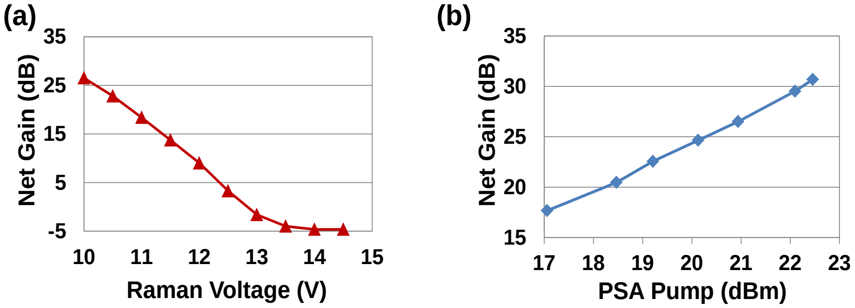

Fig. 3. (a) System net gain dependence on (a) PSA pump power and (b) Raman voltage.

The PSA black box amplifier is then compared to a commercial benchtop EDFA with ~4dB NF under different input signal power levels as shown in Fig. 4. Since the optimal amplification range of the EDFA used is limited to 1563nm while the PSA system amplifies signal at above 1566nm due to the operation range of FBG, the wavelength of the signals to be amplified are different during comparison. However, the same signal input power and net gain for each comparison is ensured. It can be seen that in Fig. 4(a), with -30dBm input signal and 26dB net gain, PSA has ~1.5dB less ASE noise level than EDFA. Similar ASE noise level reduction is also observed under -35dBm and -40dBm input signals as shown in Fig. 4(b) and Fig. 4(c). Further performance evaluation of the black box amplifier will be carried out in the future.

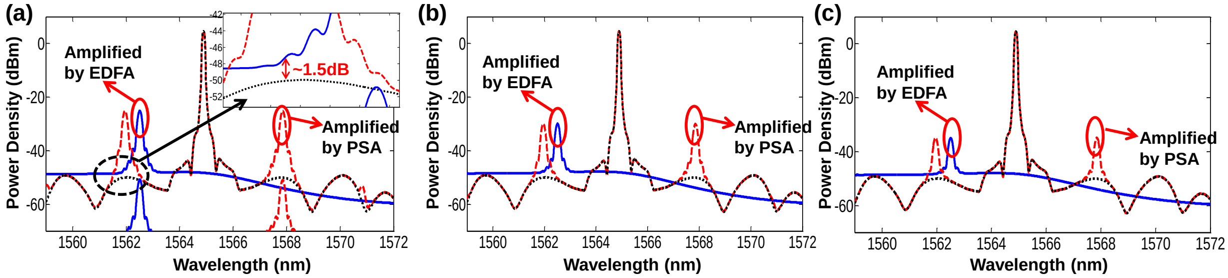

Fig. 4. ASE noise level comparison between the PSA black box amplifier and the EDFA with same net gain when the input signal power is (a) -30dBm, (b) -35dBm and (c) -40dBm. The optical spectrum analyzer (OSA) is set to have 0.1nm resolution.

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