Dynamic Properties of Double-Pass Discrete Raman Amplifier With FBG-Based All-Optical Gain Clamping Techniques

M. Tang, *Student Member, IEEE*, Y. D. Gong, and P. Shum, *Member, IEEE*

***Abstract*—The authors propose and implement a discrete fiber Raman amplifier configured in double-pass scheme together with fiber Bragg grating (FBG)-based all-optical feedback. The double-pass amplifiers achieve more than a 30-dB net gain with affordable pump power and guarantee a large margin for gain clamping. The all-optical gain clamping is provided by the lasing wavelength inside the cavity caused by the high reflectivity FBG and wide-band reflector. A stable gain is obtained for large input signal dynamic range of 30 dB. The gain variation is kept below 0.17 dB and the noise figure is flattened at the same time. Also, the authors investigate the Raman gain and noise figure as a function of signal wavelength with the proposed gain clamping technique.**

***Index Terms*—Discrete Raman amplifiers (DRA), double pass, fiber Bragg grating (FBG), gain clamping.**

I. INTRODUCTION

FIBER Raman amplification is one of the enabling technologies for next-generation long-haul and ultralong-haul high-capacity fiber optical transmission systems. Although the distributed Raman amplifiers employing the transmission line as a gain medium can be used to improve the noise figure and reduce the nonlinear penalty of DWDM systems [1], the lumped or discrete Raman amplifiers (DRA) are primarily designed to offset the loss of the dispersion-compensating module in the dispersion-managed fiber link or to open up new wavelength windows and to increase the network capacity [1], [2]. Among various discrete Raman amplifiers, the small effective-core areas and high germanium concentration of dispersion-compensating fibers (DCF) make themselves inherent components of all-Raman-amplified systems. We have developed recently a high-gain double-pass discrete Raman amplifier using DCF and high-reflectivity FBG to make such amplifiers more efficient and with affordable noise performance [3]. Besides the gain and noise performances, amplifier transients during channel add/drop or total input power variations must be suppressed in order to maintain the transmission quality of dynamic networks. All-optical feedback is one of the promising techniques to stabilize the gain of the amplifier in dynamic operation. The automatic gain control in Raman amplifiers using an additional lasing line has been investigated theoretically and experimentally [4], [5]. Furthermore, gain clamping in L-band erbium-doped fiber amplifiers (EDFAs) using a fiber Bragg grating (FBG) has been proposed to stabilize the gain of a fiber amplifier [6], and partially gain-clamped single and double-pass L-band EDFAs using FBG have been investigated experimentally in [7]. However, there has been no study on gain control mechanisms in double-pass discrete Raman amplifiers.

In this letter, we report on a new gain clamping technique in the double-pass Raman amplifier systems. The gain control is achieved using an FBG and a wide-band reflector to form a fiber laser. The high lasing power, which develops within the linear resonant cavity, makes the DRA operate in a saturation regime and provides a uniform gain and noise performance for large signal variation (both in power and in wavelength). This is the first experimental demonstration of an FBG-based all-optical gain-clamped double-pass Raman amplifier (AO-GC-DRA).

II. EXPERIMENTAL SETUP, RESULTS, AND DISCUSSIONS

Our experimental configuration is demonstrated in Fig. 1. The input signal from a tunable laser source (TLS) is injected into a 3-km DCF through the optical circulator (OC) port 1. The 1455-nm Raman fiber laser with relative intensity noise (RIN) <-124 dB/Hz is employed as the continuous wave (CW) Raman pump source and is injected through a wavelength-division multiplexer (WDM). The measured 3-dB gain bandwidth of this pump is 20 nm and the peak Raman gain wavelength is 1554 nm. A wide-band mirror with reflectivity $>90\%$ is placed at the fiber end. Thus, the signal can experience equivalent bidirectional amplification and transmit through OC port 3. The FBG has a reflectivity $>99\%$ at 1539 nm and a stopband of 0.2 nm. The amplified spontaneous emission (ASE) light within the stopband of FBG will resonate in the fiber cavity to form a lasing light. It is worth noting that the average total polarization mode dispersion (PMD) value of our DCF is measured as 0.82 ps, which is high enough to neglect the polarization dependence of the Raman gain [8] and it is possible to avoid the depolarization of the pump source. The loss of DCF is measured as 0.49 and 0.69 dB/km at 1550 and 1455 nm. The dispersion parameter at 1550 nm is -110 ps/nm/km, and the nonlinear coefficient $n_2/A_{\text{eff}} = 14.5\times10^{-10}W^{-1}$, where n_2 is fiber nonlinear index and A_{eff} is the effective core area. The signal is amplitude modulated (AM) at 300 MHz to suppress the stimulated Brillouin scattering (SBS); thus, the signal power presented in this letter is the average value.

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M. Tang and P. Shum are with the Network Technology Research Centre (NTRC), School of Electrical and Electronics Engineering, Nanyang Technological University 639798, Singapore (e-mail: tangming@pmail.ntu.edu.sg; EPShum@ntu.edu.sg).

Y. D. Gong is with the Institute for Infocomm Research, Innovation Center, Nanyang, 637723 Singapore.

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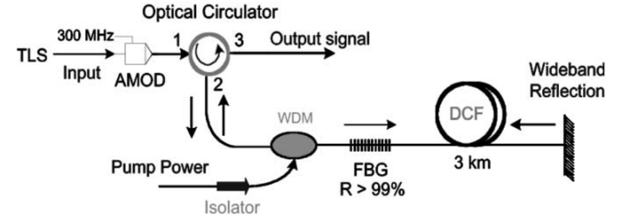


Fig. 1. Experimental setup—AMOD: amplitude modulator, TLS: tunable laser source, and WDM: wavelength division multiplexer.

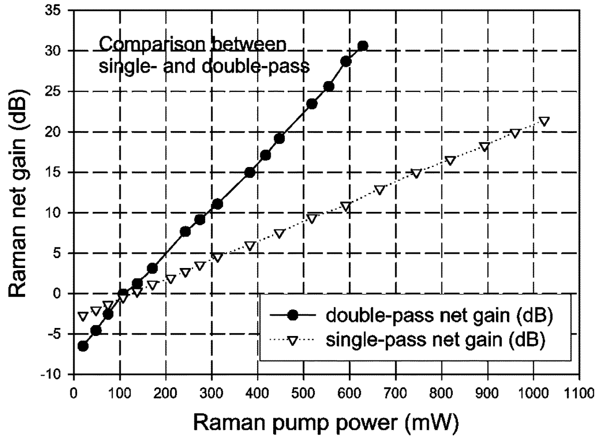
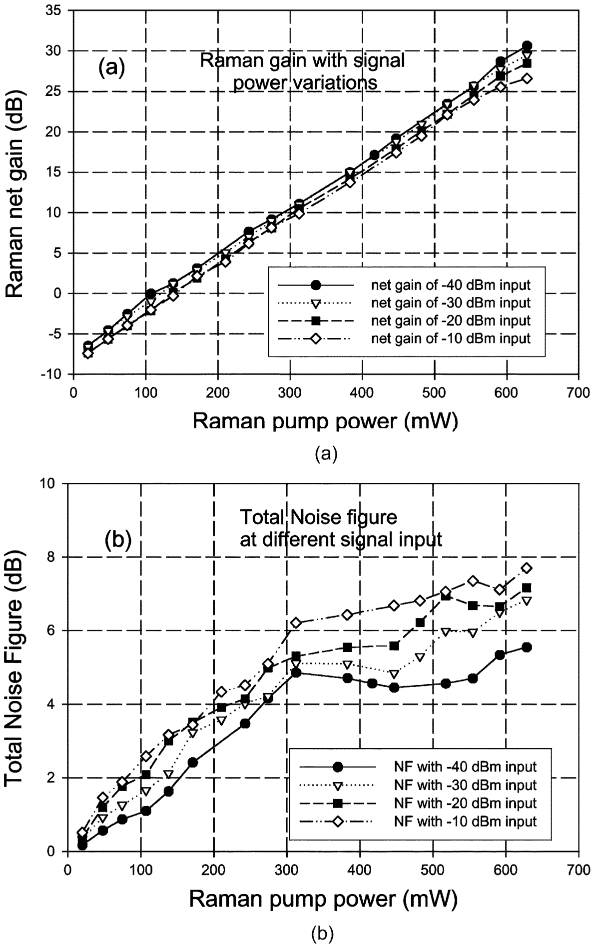


Fig. 2. Comparison of Raman net gains in single- and double-pass systems without FBG. Signal is -25 dBm at 1554 nm.

We first studied the gain performance of double-pass DRA in comparison with the typical counterpumped single-pass system. In Fig. 2, Raman net gains in the same 3-km DCF are plotted for single- and double-pass systems. The input signal is -25 dBm at 1554 nm. It is quite clear that the high-gain efficiency and low pump-power operation in the double-pass scheme make this amplifier a promising candidate to perform gain clamping since it is not practical to apply the all-optical feedback in the low gain single-pass system. Although the double-pass geometry allows the copumping when the signal first enters the amplifier, the high dispersion of DCF will average the RIN transfer; thus, performance degradation due to RIN transfer can be negligible, given our stable pump source [9]. Fig. 3 shows (a) the net Raman gain and (b) total noise figure (NF) as a function of injected pump power with different signal (1554 nm) input power levels in our double-pass system without FBG. Although more than 30-dB Raman net gain can be achieved at small signal conditions, the net gain decreases with the increasing signal input at the same pump power, which is consistent with the results in [12]. Unlike the typical single-pass amplifier, the multipath interference (MPI) noise, because of the reflected-Raman-amplified Rayleigh backscattering [3], is the major limitation factor. We measured the Rayleigh-induced noise using the expanded time-domain extinction method [10] and added it to the ASE NF using the general NF expression in [11]. As the MPI-induced noise is more strongly dependent on Raman gain, it will degrade the optical signal-to-noise ratio (OSNR), increasing the receiver sensitivity penalty, and eventually result in a noise floor. The measured total NF increases at high Raman gain region, which is consistent with the previous results [3].



(a)

(b)

Fig. 3. (a) Experimental net gain and (b) NF versus input pumping power with different input signal power. Signal wavelength is 1554 nm.

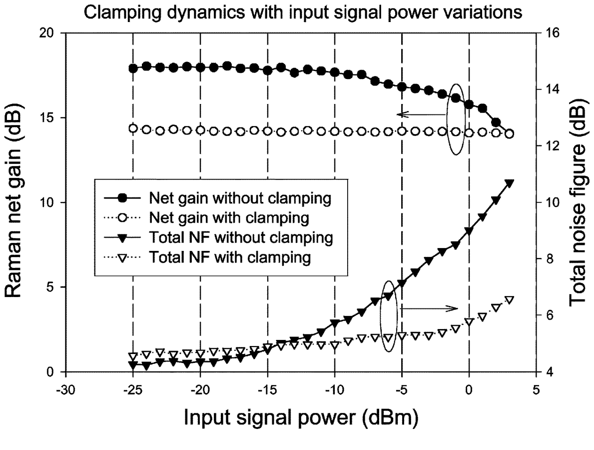


Fig. 4. Gain and NF as a function of input signal power for signal wavelength 1554 nm. Solid: without gain clamping. Hollow: with gain clamping.

We then introduce the all-optical feedback by using the high-reflectivity FBG. Gain clamping (GC) dynamics (gain and noise figure versus input power) are analyzed in Fig. 4. The pump power is fixed at 410 mW to sustain a saturation operation. Clearly, the gain-clamped double-pass amplifier maintains a stable and higher than 14-dB net gain, for the input signal power ranging from -25 to 3 dBm, while it keeps gain variation below 0.17 dB. For comparison, we plot the gain

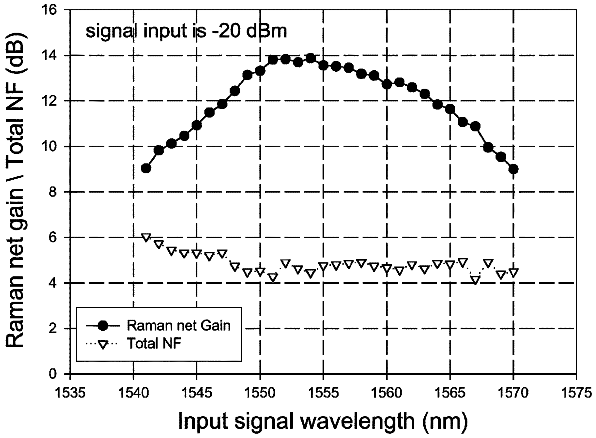


Fig. 5. Gain and NF as function of input signal wavelength when pump power is at 400 mw and the input signal power is -20 dBm.

variation versus input signal power without the GC. Although the Raman net gain at small signal input is above 17 dB, the gain experiences a significant reduction with the increasing signal input power. The gain variation without the GC is more than 3 dB. At the same time, the NF of the double-pass system without GC increases significantly with larger input signal power, thus the noise performance degrades dramatically with different input conditions. On the contrary, the NF in a double-pass system with GC can be clamped at a flat level until the input signal exceeds 0 dBm. Note that the NF with GC is larger than that without GC when a small signal is input, which coincides with the result in [4]. The larger NF in higher input power conditions is mainly due to the enhanced MPI noise in this double-pass geometry since the Rayleigh backscattering is proportional to the input signal power [3], [11]. With the lasing light in the GC amplifier, the net gain experienced by the signal and the MPI noise is clamped. The pump depletion due to the resonant cavity suppresses the total NF of GC-DRA at the large signal input. The variation of NF is below 1.5 dB in GC-DRA. Thus, our 3-km double-pass GC-DRA exhibits a stable $\sim$14 dB net gain and the total dispersion is -660 ps/nm, with an NF less than 6 dB for a 30-dB input dynamic range. This gain module is suitable for compensation of dispersion and loss in a 40-km span of standard single mode fiber (SSMF) with considerable gain margin. Fig. 5 shows the gain and total NF as a function of signal wavelength for input signal power of -20 dBm with the pump power of 400 mW. More than a 10-dB net gain can be obtained from 1542 to 1568 nm. Although the peak gain at 1554 nm decreases 4 or 5 dB compared to the results in Fig. 3(a), the 3-dB gain bandwidth of this amplifier is broadened to 25 nm. The total NF can be maintained at a flat level from 1547 to 1570 nm with a variation within 0.3 dB.

Also, the stimulated Brillouin scattering (SBS) has been suppressed in our double-pass GC Raman amplifier. Since the fiber loss is replaced by distributed gain in the Raman amplifier, both the pump and Stokes wave experience gain and the SBS threshold is drastically reduced [13]. The SBS can be further enhanced by the external reflection due to the reflector in double-pass geometry [12]. It follows from our observation that Brillouin scattering threshold depends on pump power (Raman gain) only as [13] in DRA. Without GC, strong Brillouin scattering effects are observed when pump power exceeds 660 mW, regardless of the input signal power, although the signal was modulated at 300 MHz. The lasing power generated due to all-optical feedback dominates the gain characteristics and its pump depletion eliminates the Brillouin Stokes of signal successfully in the GC scheme.

III. CONCLUSION

In summary, we have demonstrated, for the first time, an FBG-based gain-clamped double-pass discrete Raman amplifier for loss and dispersion compensation. Based on the all-optical feedback mechanism, this technique achieves a flat Raman net gain of more than 14 dB with large input power variations and keeps only a 0.17-dB gain ripple when pump power is fixed at 410 mw. The high pump efficiency of a double-pass configuration (30-dB net gain achieved at the pump power of 640 mW) provides a large margin for gain clamping. This device flattens the noise figure over large input dynamic range (power and wavelength). The gain-clamping technique eliminates the Raman-reflection-enhanced Brillouin scattering and provides a stable and efficient Raman-amplified module for the dispersion-managed fiber transmission line.

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