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All optical method to achieve gain-clamping in broadband distributed fiber Raman amplifiers

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In this paper, we proposed that using a pair of fiber gratings in a section of the transmission fiber, a gain clamped broadband distributed fiber Raman amplifiers (DRA) can easily be made based on the utilization of the pumps' interactions and uneven gain property along the fiber in the amplifier.

Keywords: fiber Raman amplifier, fiber Bragg grating, gain clamping, power transient.

1. Introduction

Broadband amplification and distributed amplification are two distinctive characteristics of Raman amplifiers (RA) revived and progressed quickly in recent years. Fiber Raman amplifiers can provide flat gain over a wide band if several pumps at various wavelengths are used together. Besides the broadband amplification, the distributed amplification, in principle, shows better system performances, especially in terms of noise [1].

But when the amplifiers are to be used in practical DWDM systems, the number and power level of the input channels may change randomly at times. Then, it is important to ensure that the equal performance of channels at different wavelengths can be achieved at a wider range of input signal power levels.

There have been reported two kinds of gain control methods for Raman amplifiers. One is monitoring the signals' power and adjusting pumps' power [2]; the other is using an all-optical feedback loop in a discrete Raman amplifier [3], [4]. But in a broadband distributed Raman amplifier (DRA), multi-pumps should be used to achieve broadband amplification; and in order to take advantage of distributed amplification, the transmission fiber is used as gain medium. This makes the dynamic gain control of broadband DRA amplifiers more difficult. The former gain control method needs complex feedback and auto pumps' power control systems to change the pumps' power. When multi-pumps are used, more than one monitoring channel should be used [2], and the cooperation of the pumps under different input conditions becomes a big problem. Also the delay of the pump's adjusting system can cause trouble as regards the amplifier's transient effects [5]. The latter method uses wavelength selective couplers, band-pass filter and the amplifier to form a ring laser structure, and takes advantage of the Raman gain to generate lasing as the gain-clamped method often used in EDFAs. When the transmission fiber is used as a gain medium, the Raman gain coefficient of transmission fiber is much lower than that of the fiber used in discrete Raman amplifiers, and the transmission fiber is too long to form a ring structure. It is impossible to make an optical loop with low attenuation for the clamped wavelength in the optical feedback loop allows lasing to be sustainable. So, the latter method can only be used in discrete Raman amplifiers.

2. Principle

Two important properties of broadband DRA are worth paying attention to. The first one is that although the net Raman gain of a distributed fiber Raman amplifier is small, the amplification occurred mainly near the end of transmission fiber where the pumps' power is high. The other important property is that there are great interactions among the pumps of the amplifier. Surely they can cause inhomogeneity in common Raman amplifiers, but they can also be utilized in clamping the amplifiers' broadband gain profile.

The uneven gain property along the fiber and the interactions among pumps make it possible to get gain-clamped DRA by a sample all optical method. For a DRA backward pumped by high power laser diodes, we use fiber Bragg gratings as reflectors near the transmission fiber's end (see Fig. 1). Then the section of the transmission fiber between the gratings becomes an optical cavity and can cause high-power lasing at the grating's wavelength. Because of this the section of fiber has high pumps' power which can give high Raman gain. The lasing operates in a saturation region of the amplifier providing uniform gain and noise performance for input signals, and the pump's interaction can help the lasing to clamp the gain in the whole band. The power of signal, spontaneous Raman emission (ASE), lasing, and some pumps along the transmission fiber of this RA are shown in Fig. 2

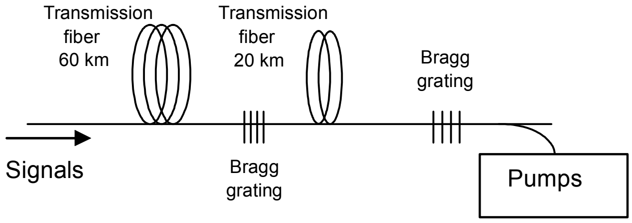

Fig. 1. Structure of all optical-gain-clamped DRA.

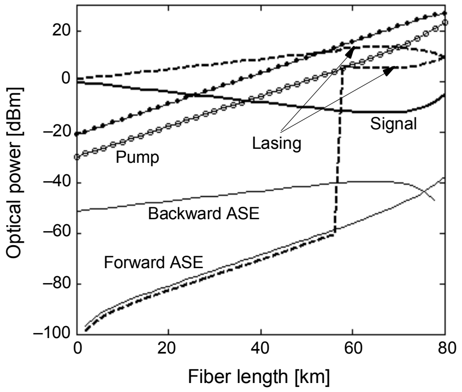

Fig. 2. Optical power in all optical gain-clamped DRA.

The structure of the gain-clamped RA is shown in Fig. 1. The wavelength of the gratings we choose is 1584 nm. Because of the gain-clamping lasing work at shorter wavelength, the lasing can act as a pump for the signals for they just fill in the Raman gain bandwidth of the lasing. Then the amplifier's gain profile will change with the lasing power. Furthermore, the lasing's ASE noise makes the noise figure higher especially for the signal channels at shorter wavelength near the lasing (due to temperature dependent spontaneous Raman emission noise[6], [7]). These effects can be avoided if the lasing wavelength is longer than that of the signals.

3. Simulation results and discussion

During the simulation we use a numerical method to resolve the differential equations of RA complete numerical model [7] that include fiber loss, pump-to-pump, pump-to -signal, signal-to-signal Raman interactions, Rayleigh scattering, spontaneous Raman emission and its temperature dependence:

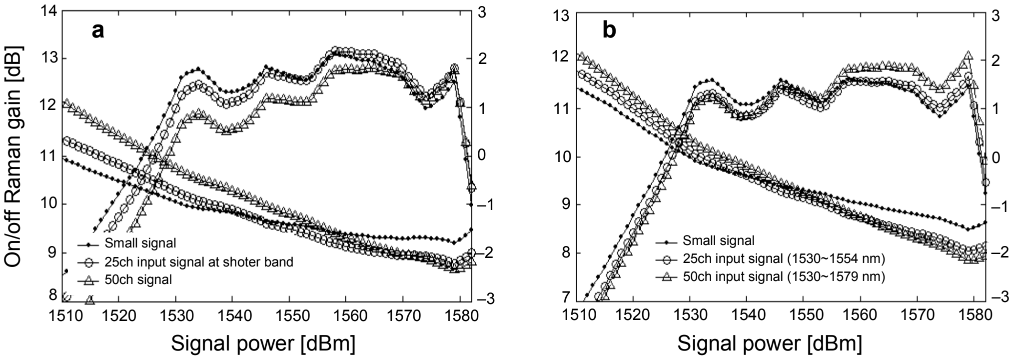

Fig. 3. Gain and NF of: **a** – DRA without gain clamping, **b** – optical gain-clamped DRA.

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\begin{aligned}
\frac{\mathrm{d}P_f(z,\,\nu)}{\mathrm{d}z} &= -\,\alpha(\nu)P_f(z,\,\nu) + \gamma(\nu)P_b(z,\,\nu) \\
&+ \int\limits_{\xi>\nu} \left\{ \frac{g_\nu}{A_{\mathrm{eff}}}(\nu-\xi)\Big[P_f(z,\,\xi)+P_b(z,\,\xi)\Big]P_f(z,\,\nu) \right. \\
&\left. + 2h\nu\frac{g_\nu}{A_{\mathrm{eff}}}(\nu-\xi)\Big[P_f(z,\,\xi)+P_b(z,\,\xi)\Big]\left[1+\frac{1}{\exp\left[\dfrac{h(\xi-\nu)}{KT}\right]-1}\right]\right\}\mathrm{d}\xi \\
&- \int\limits_{\xi<\nu} \left\{ \frac{g_\nu}{A_{\mathrm{eff}}}(\nu-\xi)\Big[P_f(z,\,\xi)+P_b(z,\,\xi)\Big]P_f(z,\,\nu) \right. \\
&\left. + 2h\nu\frac{g_\nu}{A_{\mathrm{eff}}}(\nu-\xi)\Big[P_f(z,\,\xi)+P_b(z,\,\xi)\Big]\left[1+\frac{1}{\exp\left[\dfrac{h(\xi-\nu)}{KT}\right]-1}\right]\right\}\mathrm{d}\xi
\end{aligned}
$$

where: $P_f(z,\ \nu)$ – forward power at frequency ν and distance z; $P_b(z,\ \nu)$ – backward power at frequency ν and distance z, $\alpha(\nu)$ – attenuation; $\gamma(\nu)$ – Rayleigh scattering coefficient; $g_r(\Delta\nu)g_r(\xi-\nu)$ – Raman gain coefficient between frequencies ξ and ν; A_{eff} – effective area of the fiber; h – Plank's constant, K – Boltzman's constant, T – temperature of the fiber.

First, a common RA without gain-clamped method was investigated by simulation. The Raman amplifier is backward-pumped by three LDs at different wavelengths (see the Table) to get flat gain profile in 1530–1580 nm. The transmission fiber used as the gain medium is a standard single mode fiber. The gain and noise figures for different

Table. Pump configurations for the conventional RA and gain-clamped RA (GCRA).

Pump wavelength [nm]	Pump power [mW] (conventional RA)	Pump power [mW] (GCRA)
1420	200	220
1435	180	200
1468	490	470

input conditions are shown in Fig. 3**a**. The gain profile for small signal is very flat (gain ripple is ±0.6 dB). When the input signals change to 50 channels (at the wavelength from 1530 to 1579 nm with 1 nm channel spacing and signal power 1 mW/channel) from results obtained by numerical simulations we can clearly see the gain profile changes (Fig. 3**a**). The gain profile becomes tilt. The gain at shorter wavelength decreases more seriously. The gain variation for 1530 nm is more than 1 dB. Even when the total power of input channels is the same, the different wavelengths of the input channels can cause the gain profile to differ. This phenomenon makes the gain clamping of RA more complicated when the monitoring and adjusting method is used.

Figure 3**b** shows the simulation results for the gain-clamped RA (the FBG at the receiver end has 1 nm bandwith and 99% reflection ratio at center wavelength 1584 nm, and the FBG inserted in the transmission fiber 20 km away from the output end has 20% reflection ratio) under the same input conditions with the conventional RA that has been disused above. Different input conditions do have very small effect

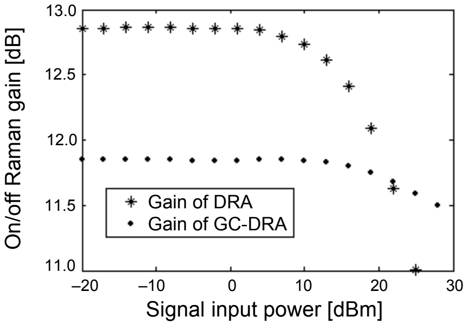

Fig. 4. On/off gain *vs.* signal input power for RA with and without gain-clamping.

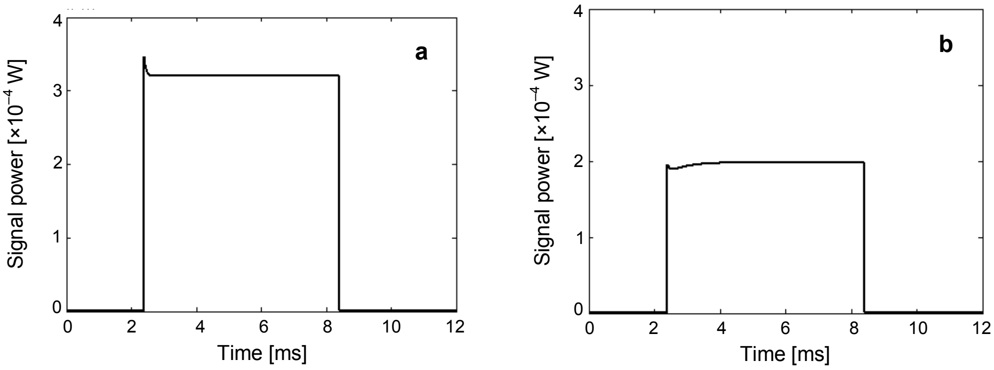

Fig. 5. Adding/dropping channel in: **a** – conventional DRA, **b** – gain-clamped DRA.

on the gain profile and the noise figure; and the gain variation is less than 0.3 dB for all input conditions. The simulated gain saturation properties at different wavelengths of RA with and without gain clamping are shown in Fig. 4. The gain saturation properties have obviously been improved for the amplifier with the gain clamping method we proposed. Compared to the RA without pump clamping using the same total pump power, the decrease of the gain of the gain clamped amplifier is less than 1.5 dB.

The transient effects of the gain clamped distributed Raman amplifiers have also been analyzed by numerical method [8]. The surviving channel is at 1530 nm and the other 49 channels at 1531–1579 nm are adding/dropping channels, the power of the input signals is 1 mW/channel. Figures 5 and 6 show the simulation results of power transient of a conventional distributed Raman amplifier and the distributed Raman amplifier using the gain clamping method we have introduced. The lasing power (Fig. 7 shows the calculated lasing power before the FBG near the output end) for such an amplifier changed automatically to keep the gain stable. From the figures we can see that the transient effects of RA have been improved by means of using the gain clamping method (power variation of surviving channel decreases from 0.5 mW to

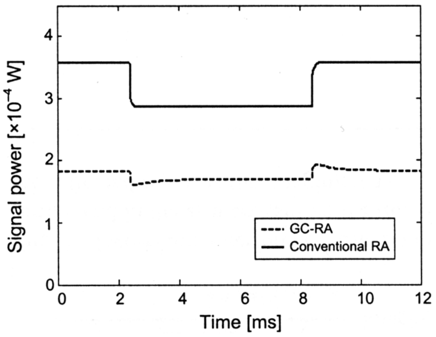

Fig. 6. Surviving channel in conventional DRA and gain-clamped DRA.

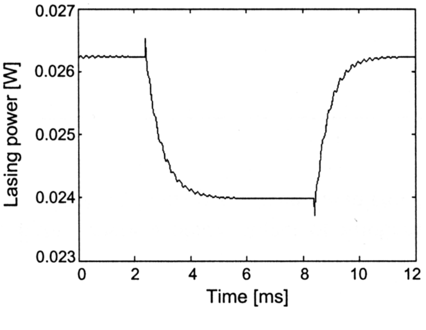

Fig. 7. Lasing power in all gain-clamped DRA.

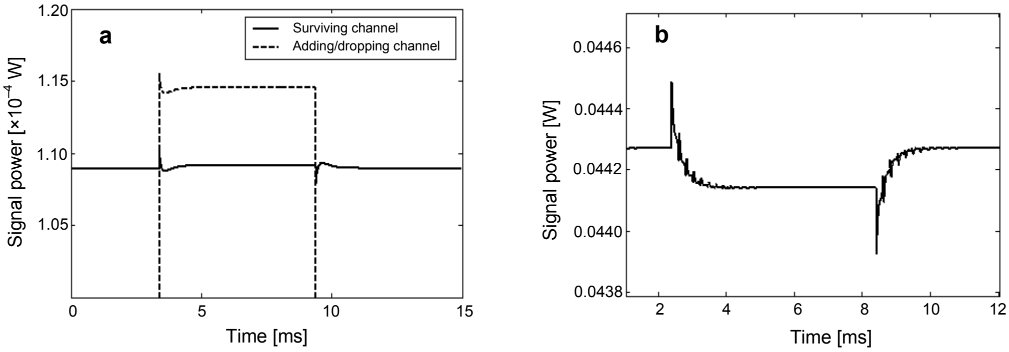

Fig. 8. Signal power of gain-clamped DRA (**a**) and lasing power of gain-clamped DRA (**b**).

less than 0.15 mW). The overshot of adding channel and the power fluctuation of surviving channel have been suppressed efficiently. Through changing the fiber grating's wavelength or reflectivity, the degree of gain clamping can be adjusted conveniently. Figure 8**a**, **b** show simulated results of the signal and lasing power of a RA with high degree gain clamping, from which we can see that the signal power of this RA is more stable, but the lasing power is higher and thus makes the amplifier have lower gain efficiency.

4. Conclusions

In summary, we have demonstrated a simple all optical method to get broadband distributed Raman amplifiers. The realization of the method is based on the uneven gain property and pumps' interactions. Using this method the gain variation can be reduced effectively. It is a promising method to be used in broadband distributed fiber Raman amplifiers for it needs no complex monitor and control systems.

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