Experimental demonstration of output power spectrum clamping for multi-channel backward-pumped distributed fiber Raman amplifiers

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Output power spectrum clamping over C+L band (84 channels) is demonstrated experimentally on a standard 100-km single mode backward-pumped distributed fiber Raman amplifier (B-DFRA). The clamping is realized by pump adjustment based on a simple linear relation of individual pump power versus on-off gain level and gain tilt in its spectrum. The average clamping error over all channels are less than 0.32 dB within the experimental range.

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Backward-pumped distributed fiber Raman amplifier (B-DFRA) has been one of the key technologies for high capacity long-haul dense wavelength division multiplexing (DWDM) systems, where a very important issue is to make all the signal channels have the same performance in terms of power, signal-to-noise ratio (SNR) as well as Q-factor. In the new generation optical networks, the signal power is not constant if some channels are add/dropped or path loss is changed as the system reconfiguration[1]. It is well known that the net gain of a Raman amplifier depends not only on the fiber loss and pump-to-signal Raman scattering (PSRS), but also on the signal-to-signal Raman scattering (SSRS) due to the longer wavelength channels amplified in expense of shorter wavelength channels. SSRS will cause output spectrum distortion as the signal power variation and may increase inter-channel power divergence and SNR penalty, especially in cascaded systems. It has been pointed out that SSRS distortion is always linear tilt on a decibel/nanometer scale[2], so one potential approach to compensate this SSRS distortion is to create a proper on-off gain with suitable level and tilt. Previously, we present numerically and experimentally a simple linear relation of individual power at each pump wavelength versus on-off gain and gain tilt, based on which any required on-off gain level and gain tilt can be achieved by pump adjustment[3]. In this letter, by using this relation, an output power spectrum clamped B-DFRA with five pump-wavelengths and 84 signal channels is demonstrated experimentally. The average clamping error achieved over all channels is less than 0.32 dB while the total input power varies from 13 to 19 dBm with all channels on, or either all C- or L-band channels dropped. To our knowledge, this is first reported on multi-channel output power spectrum clamped B-DFRA.

In a B-DFRA, the output power of kth signal channel is determined by four factors, and can be written in logarithmic scale as[4]

$$P_k^{\text{out}} = P_k^{\text{in}} + G_k^{\text{on-off}} + G_k^{\text{SSRS}} + L_k, \qquad (1)$$

where P_k^{in} is the input signal power, L_k is the fiber background loss, $G_k^{\text{on-off}}$ is the on-off gain from PSRS, and G_k^{SSRS} is the gain /loss due to SSRS distortion. Practically, B-DFRA often operates in small signal range with low net gain (typically -10 dB), then one can accept an approximation that $G_k^{\text{on-off}}$ is determined only by pump powers, while G_k^{SSRS} is determined only by signal powers. When re-configuration happens, there may be a channel power variation of ΔP^{in} due to path loss change or a channel number change of ΔM due to channels add/drop; both of them will cause a SSRS variation ΔG_k^{SSRS}. As no pump power adjustment, the output power will suffer a variation,

$$\Delta P_k^{\text{out}} = \Delta P^{\text{in}} + \Delta G_k^{\text{SSRS}}, \quad k = 1, \cdots, M + \Delta M, \qquad (2)$$

where M is the channel number before re-configuration. According to the linear evidence observed in Ref. [2], the SSRS tilt T can be described by the power difference between the longest and shortest signal wavelengths. Then, the variation of output power over whole residual spectrum ranges can be described by an average level and tilt variations

$$\Delta P_{\text{ave}}^{\text{out}} = \frac{1}{M + \Delta M} \sum_{k=1}^{M+\Delta M} \Delta P_k^{\text{out}},$$

$$\Delta T^{\text{out}} = \left[\Delta P_{M+\Delta M}^{\text{out}} - \Delta P_1^{\text{out}}\right]. \qquad (3)$$

To keep the output power of residual channels constant, pump power adjustment is required to achieve a proper on-off gain with reversed average level and tilt: $\Delta G_{\text{ave}}^{\text{on-off}} = -\Delta P_{\text{ave}}^{\text{out}}$, $\Delta T^{\text{on-off}} = -\Delta T^{\text{out}}$. It has been demonstrated that the pump power[3] at wavelength of $14xx$ nm has a approximately linear relation to the on-off gain level G and gain tilt T as $P_{14xx} = K_1 \times T + K_2 \times G + K_3$, where K_1, K_2 and K_3 are the constants to be obtained by measurement data fitting. So, the required pump power adjustment amount can be easily derived as

$$\Delta P_{14xx} = K_1 \times \Delta T^{\text{on-off}} + K_2 \times \Delta G_{\text{ave}}^{\text{on-off}}. \qquad (4)$$

In principle, if any signal variation happens, the pump powers can be adjusted by using Eqs. (3) and (4). But a serious problem is that the constants K_1 and K_2 are

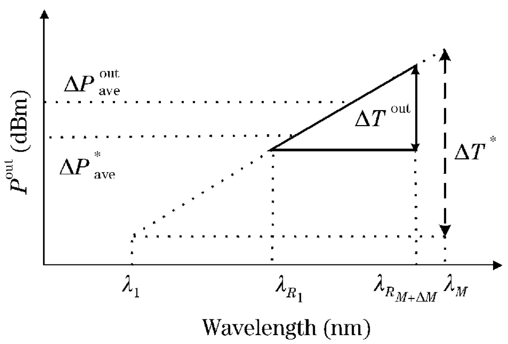

Fig. 1. Schematic diagram of the output spectrum variation extended from residual range to the full range.

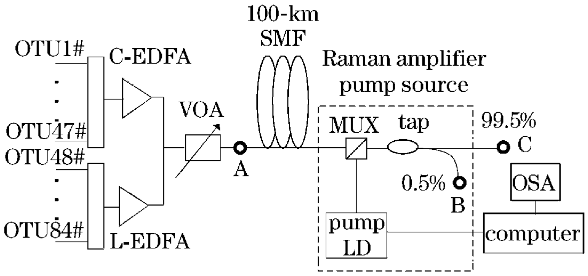

Fig. 2. Experimental setup.

related to both pump and signal wavelengths, which means that different constants are required for different residual signal channels. A more practical approach is always to use the constants with full signal channels loading, and to always extend the residual output spectrum to the whole signal wavelength range. The schematic variation of output power spectrum is shown in Fig. 1, where λ_1 /λ_M is the shortest/longest signal wavelength, supposing the system has M channels in maximum. After re-configuration, the residual signal channels cover only the wavelength range of $\lambda_{R_1} - \lambda_{R_{M+\Delta M}}$. By applying geometry, the variation level and tilt in Eq. (3) should be transformed into ΔP^*_{ave} and ΔT^* as

$$\Delta P^*_{\text{ave}} = \Delta P^{\text{out}}_{\text{ave}} - \frac{\Delta T^{\text{out}}}{2}\left(\frac{\lambda_M + \lambda_1 - 2\lambda_{R_1}}{\lambda_{R_{M+\Delta M}} - \lambda_{R_1}} - 1\right),$$

$$\Delta T^* = \frac{\lambda_M - \lambda_1}{\lambda_{R_{M+\Delta M}} - \lambda_{R_1}} \times \Delta T^{\text{out}}. \qquad (5)$$

Then the constants obtained under full signal channels loading condition are applied.

To validate the power clamping method proposed above, a set of experiments are carried out. The experimental setup is shown in Fig. 2. The gain medium is standard 100-km single mode fiber (SMF) pumped by five polarization-multiplexed pumps at the wavelengths of 1423, 1433, 1443, 1463, and 1493 nm. The transmitter has totally 84 channels ($M = 84$) in the wavelength range from 1529.13 to 1602.69 nm (denoted by #1−#84). The C-band (#1−#47) and L-band (#47−#84) channels are boosted respectively by two EDFAs and combined by a C/L WDM multiplexer. A variable optical attenuator (VOA) is placed before the SMF to vary the input signal power. The output spectra at point C or B are measured by the optical spectrum analyzer (OSA) and the data are treated by the computer. Since the splicing loss cannot be measured actually, so all the pump powers reported in this letter are the pigtail values according to the drive currents and the calibration of P-I curves, since this has no effects on the results.

First of all, the total input power is set at 17 dBm (point A) with 2-dB VOA attenuation. In our experiment, the pumps are adjusted carefully to set the output power at about -18 dBm per channel (i.e. 7.5 dB on-off gain). The pump powers are 160, 80, 160, 80 and 160 mW, respectively. The output spectrum measured at point C is recorded as standard for comparison later. To obtain the constants K_1 and K_2 for each pump wavelength, the pump powers are adjusted to get different output spectra, the data of gain level, gain tilt, and the corresponding pump powers are used in data fitting. The fitting results are listed in Table 1.

Then, two groups of experiments are carried out. Firstly, the VOA is adjusted so that the total input signal power varies from 13 to 19 dBm. The output spectra are shown in Fig. 3(a) when the input power is respectively

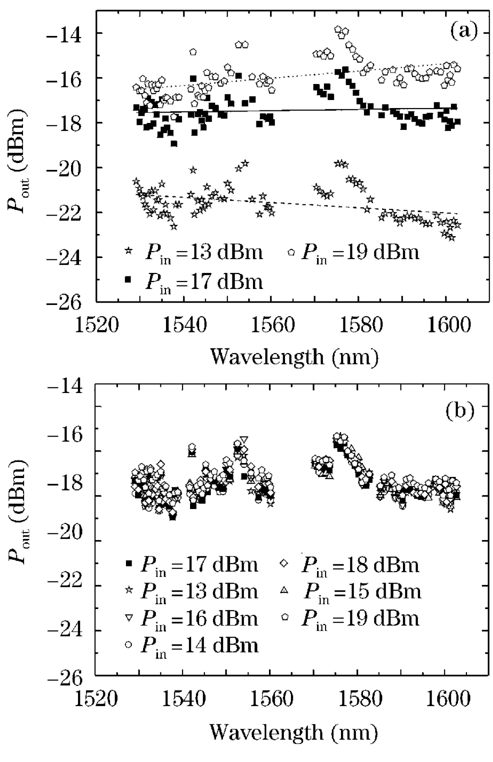

Fig. 3. Measured output spectra at different total input power levels without (a) and with clamping (b).

Table 1. Regression Results of Constants K_1 and K_2 for Each Pump Wavelength

Wavelength (nm)	1423	1433	1443	1463	1493
K_1	22.9087	16.0551	21.1979	9.6230	11.6729
K_2	−7.7986	−11.9665	−10.9839	−0.5774	19.3812

Table 2. Summary of the Required On-Off Gain Level and Tilt and the Residual Variations & Errors after Clamping

Total Input	Before Clamping		After Clamping		
Power (dBm)	ΔP^*_{ave} (dB)	ΔT^*(dB)	ΔP^*_{ave}(dB)	ΔT^*(dB)	Average Error (dB)
13	−4.13	−1.06	−0.09	0.1	0.25
14	−3.21	−0.67	−0.13	0.05	0.21
15	−2.19	−0.53	−0.03	−0.08	0.23
16	−1.2	−0.33	0.03	−0.1	0.18
17	0	0	0	0	0
18	0.57	0.63	0.15	−0.1	0.20
19	1.48	0.98	0.27	−0.15	0.32
19, C-Band only	2.33	−0.63	0.06	0.07	0.29
19, L-Band only	1.43	−1.33	0.05	0.07	0.18

13 and 19 dBm with the standard curve at 17 dBm input, where the SSRS distortion on level and tilt can be seen clearly. The un-flat output spectra mainly come from the imperfect transmitter, and partially from the un-equal Raman gain. The measured spectra are treated by linear fitting and the results are shown in Table 2. Then the required $\Delta G^{\text{on-off}}_{\text{ave}}$ and $\Delta T^{\text{on-off}}$ are calculated by Eq. (3). It can be seen that the more the input power drifts from the standard of 17 dBm, the higher the variations of level and tilt is. To compensate the variation, the pump powers are adjusted according to Eq. (4) with the constants in Table 1. The output spectra after pump adjustment are shown in Fig. 3(b). The residual distortion ΔP^*_{ave} and ΔT^* due to incomplete compensation are calculated, again by using Eq. (3), as shown also in Tabel 2. The averaged errors are shown in the last column of Table 2, which are defined as the absolute difference between the clamped and standard spectra. The residual ΔP^*_{ave} and ΔT^* are in the range of −0.09−0.27 dB and 0.1−0.15 dB, respectively. The averaged error over all the channels is less than 0.32 dB. Comparing to the values before clamping, it is evident that the output power spectrum is clamped successfully.

The second group of experiment is carried out with 0-dB VOA attenuation, while the C-band or L-band booster is turned off, respectively. Similar pump power adjustments and output spectra measurements are repeated with the output distortion calculated by Eq. (3) and (5). The spectra before and after clamping with the standard curve are shown in Fig. 4, where similar clamping effect can be seen. The distortion data before/after clamping are shown in the last two rows of Tabel 2. ΔP^*_{ave} is reduced from 2.33/1.43 to 0.06/0.05 dB and the value of ΔT^* is reduced from 0.63/1.33 to 0.07/0.07 dB after clamping, while the average error is less than 0.29 dB.

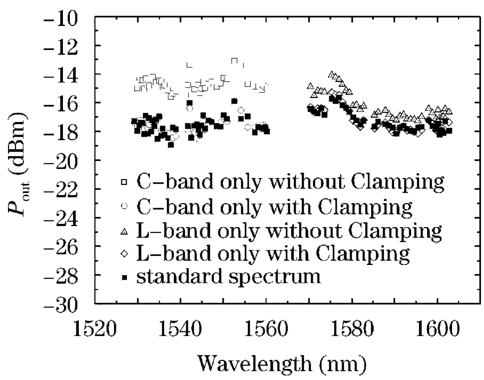

Fig. 4. Measured output spectra without/with clamping while C- or L-band signals dropped respectively, comparing with the original standard spectrum.

By considering the SSRS distortion as channel add/drop or channel power variation, an output power spectrum clamping based on a simple linear relation of individual pump power versus on-off Raman gain level and gain tilt is demonstrated experimentally. The experiments are carried out on a five-wavelength backward pumped standard 100-km SMF, while the average clamping error is less than 0.32 dB within the experimental range.

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