A novel control method for on-off gain and gain tilt of fiber Raman amplifiers

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Considering spectrum tilt due to signal-to-signal Raman scattering (SSRS) in backward distributed fiber Raman amplifiers (B-DFRA), an inverse tilted on-off gain profile is adopted to achieve flat net gain. A simple approximate linear relationship of pump power at each wavelength versus on-off gain level and tilt was derived numerically and experimentally so that a novel control method was established. Since there are only 3 pre-determinable constants required for individual pump wave, it is easy to be realized. As an example, maximum errors less than 0.2 and 0.4 dB respectively for average gain and gain tilt were achieved over C+L band in 100-km back-pumped standard single-mode fiber (SMF) experimentally.

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Recently, multi-pump backward distributed fiber Raman amplifier (B-DFRA) has been recognized as a key technique to improve the performance of high capacity, long haul optical fiber transmission systems[1]. Lots of works have been reported to improve the gain bandwidth and spectrum flatness by optimizing the pump wavelengths and powers. Meanwhile, the issues related to its dynamic properties and gain spectrum control have growing attractions and a few researches have been published[2,3]. In our previous work, a simple algorithm for flat gain spectrum adjustment was proposed in which an $M \times N$ (channel numbers × pump numbers) matrix was used to relate the pump powers and the gain spectrum[4].

For a distributed fiber Raman amplifiers, besides the gain from pump-to-signal Raman scattering (PSRS) and fiber background losses, there is still another factor to affect the gain profile. Bigo *et al.*[5] pointed out that, in a 32-channel 100-km non zero dispersion shifted fiber (NZDSF) transmission system, as high as 2-dB spectrum tilt could occur even without any Raman pump applied. This is because the longer-wavelength channels amplified in expense of the shorter-wavelength channels, which is so-called signal-to-signal Raman scattering (SSRS). Obviously, taking this SSRS spectrum tilt into account, the gain profile from PSRS should be tilt with an inverse slope respect to that of SSRS, rather than flat[6]. However, all of the previous mentioned works on gain control were concentrated on a flat PSRS gain profile, which is valid only when the SSRS effect is neglectable.

Generally, a transmission system is optimized at certain signal level with a flat net gain. Then, when some signal channels added/dropped or the channel powers decreased/increased, the net gain spectrum will tilt due to SSRS tilt. This tilt variation can, if not being corrected, result in optical signal-to-noise ratio (OSNR) penalty and increase power divergence. So it is necessary to dynamically control PSRS gain in both level (average value) and tilt for keeping un-variation net gain, especially for wide-band and ultra-long haul transmission systems.

In this letter, starting from the idea of creating and controlling a tilted PSRS gain (i.e. on-off gain) profile to achieve flat output spectrum, the relationship of pump power at each wavelength versus on-off gain level and tilt is investigated, a linear relationship is derived by numerical simulation and demonstrated experimentally respectively.

In a B-DFRA with N pump waves and M signal waves, the net gain of the kth signal channel is given in logarithm scale by Ref. [6]

$$G_k^{\mathrm{net}} = 4.343\,(-\alpha_k L) + 4.343\left(\sum_{j=N+1}^{N+M} g_{jk} \int_0^L P_j(z)\mathrm{d}z\right) + 4.343\left(\sum_{j=1}^{N} g_{jk} \int_0^L P_j(z)\mathrm{d}z\right), \tag{1}$$

where P_j represents the pump power with $j = 1, \cdots, N$ or signal power with $j = N+1, \cdots, N+M$ respectively, g_{jk} represents the gain coefficient of kth signal wave derived from jth pump wave, L is the span fiber length, and $-\alpha_k$ is the attenuation coefficient of the fiber. The three terms in right hand side (RHS) of Eq. (1) are corresponding to the fiber loss, gain tilt due to SSRS, and on-off gain from PSRS, respectively.

Practically, a B-DFRA is operated under small signal region where the pump depletion can be neglected, so that the PSRS is determined mainly by all the pump power evolution along the fiber. On the other hand, the net gain is usually low (typically -10 dB), and the output signal power is much lower than the input power, so that the SSRS is determined mainly by the input signal power. Then, we can treat the SSRS and PSRS processes as independent from each other.

It has been found out experimentally and analytically that the spectral distortion introduced by SSRS is always linear on a decibel/nanometer scale[5,7]. The distortion value depends on the total launched signal power and effective fiber length, and can be expressed as a tilt T (dB)

$$\begin{aligned} T &= 10\log\left(\frac{P_{N+M}}{P_{N+1}}\right) \\ &= 4.343\beta J_0 L_{\mathrm{eff}}(\lambda_{N+M} - \lambda_{N+1}). \end{aligned} \tag{2}$$

Here $J_0 = \sum_{i=N+1}^{N+M} P_{j0}$ is the sum of signal power launched into the fiber, $L_{\text{eff}} = \frac{1-\exp(-\alpha_s L)}{\alpha_s}$ is the effective fiber length for signals with equal attenuation α_s, $\beta = \frac{g_{jk}}{\lambda_j - \lambda_k}$ is the gain coefficient per nanometer, and the Raman gain profile is assumed to be triangular for any two channels with spacing less than 120 nm.

For a multi-channel system with equal input channel power, the SSRS gain at each channel may be plus or minus. Among them there must be a channel with 0-dB SSRS gain, for which the wavelength (defined as λ_0) can be calculated from Ref. [7]

$$\lambda_0 = \ln \frac{\exp\left[\beta J_0 L_{\text{eff}} \left(\lambda_{N+M} - \lambda_{N+1}\right)\right] - 1}{\beta J_0 L_{\text{eff}} \left(\lambda_{N+M} - \lambda_{N+1}\right)} + \lambda_{N+1}. \quad (3)$$

By using approximations of $\exp x \approx 1 + x + \frac{1}{2}x^2$ and $\ln(1 + x) \approx x$, Eq. (3) can be rewritten as $\lambda_0 = \frac{\lambda_{N+M}+\lambda_{N+1}}{2}$. Up to now, the linear distortion of SSRS is settled by T and λ_0. Then the second term in Eq. (1) can be expressed by tilt T as

$$4.343\left(\sum_{j=N+1}^{N+M} g_{jk} \int_0^L P_j(z)\mathrm{d}z\right) = \left(\frac{\lambda_k - \lambda_{N+1}}{\lambda_{N+M} - \lambda_{N+1}} - \frac{1}{2}\right)T. \quad (4)$$

For a given target gain $G^{\text{trgt}} = G^{\text{net}} + 4.343 \times (\alpha_s L)$, the required on-off gain can be derived from Eq. (1) that

$$4.343\left(\sum_{j=1}^{N} g_{jk} \int_0^L P_j(z)\mathrm{d}z\right)$$
$$= G^{\text{trgt}} + \left(\frac{\lambda_k - \lambda_{N+1}}{\lambda_{N+M} - \lambda_{N+1}} - \frac{1}{2}\right)T,$$
$$k = N + 1, \cdots, N + M. \quad (5)$$

Practically, the target gain level should be assigned by system requirement, the gain tilt can be easily measured at the fiber output end when the pump is off. Then the gain profile can be controlled following Eq. (5) by properly choosing the pump power combination. Unfortunately, the calculation for sum and integration of pump powers is still inconvenient. To solve the direct relationship of individual pump powers versus gain level and tilt, further investigation was carried out numerically and experimentally.

The simulation study was based on a 100-km single-mode fiber (SMF) pumped by four depolarized pumps at the wavelengths of 1425, 1443, 1463, and 1493 nm, respectively, on which ~80-nm flat gain from 1528 to 1605 nm was achievable. A simplified equation of Ref. [6] was adopted to calculate the evolution of pumps and signals and the least-square method was adopted to determine if the pump powers were optimized. Here, optimization means that minimum deviation from the desired gain profile is achieved. Measured fiber parameters such as Raman gain coefficients and attenuations for SMF at different wavelength were used. For any peaks of assigned gain level and tilt, the optimized pump powers at individual wavelengths were found out.

Some simulation results of individual pump powers versus required on-off gain and gain tilt are shown in Figs. 1(a)–(d). What surprising in Fig. 1 is that, all the data for each pump wavelength almost lie in a flat plane, so that they can be fitted by a two-dimensional (2D) linear approximation as

$$P_{14xx} = K_1 \times T + K_2 \times G^{\text{trgt}} + K_3, \quad (6)$$

where K_1, K_2, and K_3 are the constants of linear regression. The resulted values of $K_1 - K_3$ with the correlation factor of R^2 for each pump wavelengths (data treated via Matlab 6.1) are shown in the columns "Sim" of Table 1. Within the considered range of gain level $(3 - 15$ dB) and tilt $(0 - 8$ dB), R^2 for 1425, 1443, and 1463 nm are higher

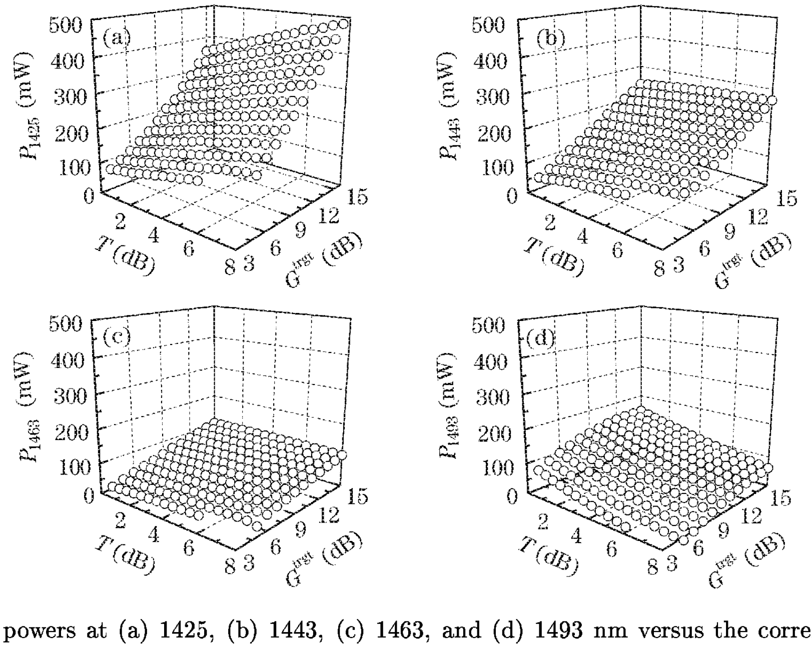

Fig. 1. Optimized pump powers at (a) 1425, (b) 1443, (c) 1463, and (d) 1493 nm versus the corresponding on-off gain and gain tilt.

than 99%, and that for 1493 nm is higher than 96%, which means that the linear approximation of Eq. (6) has good accuracy. A similar simulation result was also achieved on G.655 (Lucent TrueWave) fiber.

The experimental setup is shown in Fig. 2, where the pump wavelengths and fiber length were same as that in the simulation study. A 99:1 tap was used to monitor the pump powers. Two amplified spontaneous emission (ASE) sources of C-band (1528 – 1560 nm) and L-band (1568 – 1605 nm), combined by a C/L wavelength division multiplexing (WDM) coupler with total power below 0 dBm, were used as probe signal. An optical spectrum analyzer (OSA), at the output end of the fiber, was used to measure the on-off gain while the pumps were on and off.

First of all, the constants of $K_1 - K_3$ for each pump wavelength were determined from experimental data. By setting the pump powers randomly, a corresponding gain profile could be obtained. The gain profile could be improved to approach some gain level and tilt with a gain ripple as minimum as possible, if the pump powers were adjusted carefully. One of the optimized on-off gain spectra with 12-dB average gain and 6-dB gain tilt is shown in Fig. 3, the pump powers were 400.0, 319.4, 89.4, and 90.5 mW, respectively.

Once the gain spectrum was optimized, the on-off gain level, tilt and the powers at each pump wavelength were noted down. The measurement was repeated at different gain and gain tilt values and 35 groups of results are shown in Fig. 4. Similar to the simulation result, the data for each pump wavelength also lie almost in a plane. The linear regression results of constants $K_1 - K_3$ (via Matlab 6.1) with R^2 are shown in columns "Exp" of Table 1. All the correlation factors R^2 were higher than 97.7%. The difference between experiment and simulation may be mainly caused by inaccurate measurement of fiber parameters.

After the constants of $K_1 - K_3$ were obtained, the powers of individual pump wavelength for any assigned target gain level and tilt can be determined by using Eq. (6), and then a corresponding on-off gain spectrum can be measured. Six examples of measured spectra over the wavelength range from 1529 to 1605 nm are shown in Fig. 5, with the corresponding assigned target gain, gain tilt, and the measured data (G^m, T^m). The errors of measured data with respect to the target are less than 0.2 and 0.4 dB within the investigated range of 8 – 14 and 0 – 6 dB, respectively.

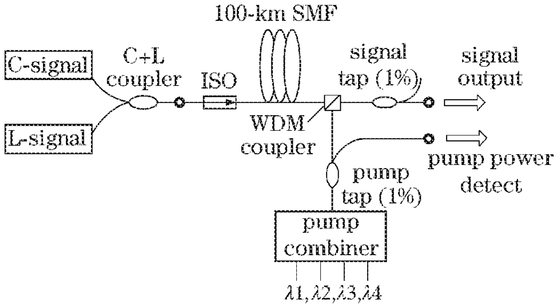

Fig. 2. Experimental setup.

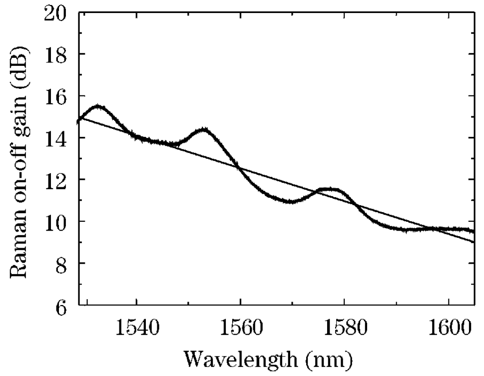

Fig. 3. One of the optimized on-off gain spectrum with 12-dB average gain and 6-dB tilt, the straight line is the target gain.

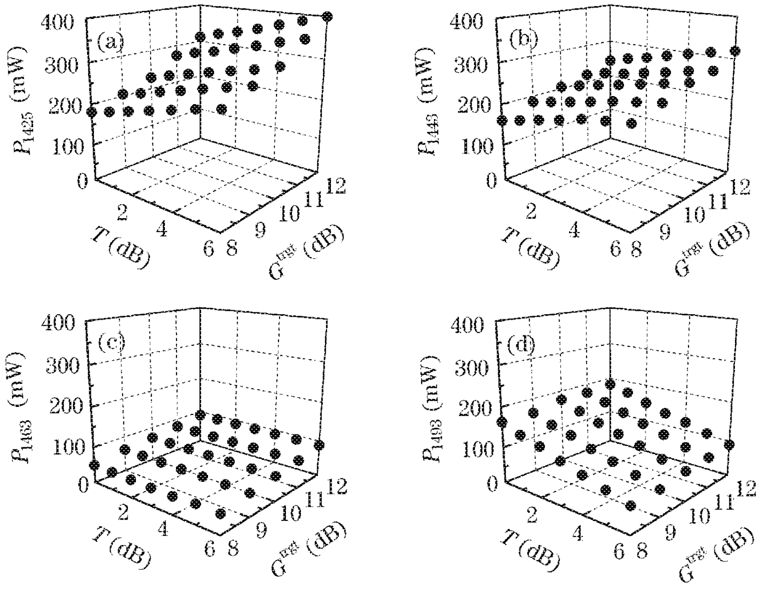

Fig. 4. The measured pump powers for wavelength of (a) 1425, (b) 1443, (c) 1463, and (d) 1493 nm versus average gain and gain tilt when minimum of gain ripple achieved.

Table 1. Regression Results of Constants $K_1 - K_3$ and Correlation Factor from Simulation and Experiment Data

	K_1		K_2		K_3		R^2	
	Sim	Exp	Sim	Exp	Sim	Exp	Sim	Exp
P_{1425}	33.5987	14.311	27.5548	36.588	−2.0397	−56.352	0.995	0.991
P_{1443}	8.4721	11.966	11.7953	19.587	−13.7879	−10.984	0.997	0.988
P_{1463}	3.2190	−0.0001	6.9012	7.7707	−22.7911	−12.8354	0.988	0.977
P_{1493}	−7.7960	−15.295	12.7470	5.7009	−23.7962	−27.034	0.961	0.995

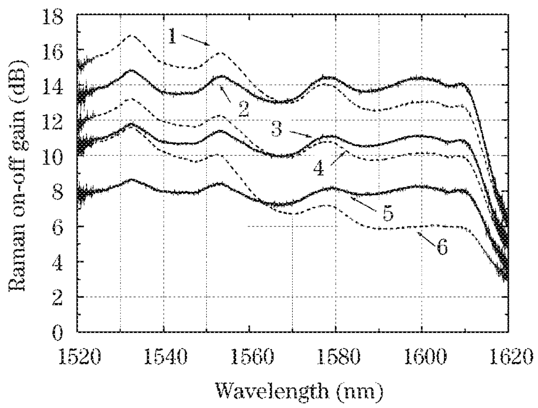

Fig. 5. The measured Raman on-off gain spectra while the pump powers were set by Eq. (7). Curve 1: $G^{\mathrm{trgt}} = 14$ dB, $T = 4$ dB, $G^{\mathrm{m}} = 13.9$ dB, $T^{\mathrm{m}} = 3.6$ dB; 2: $G^{\mathrm{trgt}} = 14$ dB, $T = 0$ dB, $G^{\mathrm{m}} = 13.8$ dB, $T^{\mathrm{m}} = 0.1$ dB; 3: $G^{\mathrm{trgt}} = 11$ dB, $T = 0$ dB, $G^{\mathrm{m}} = 11.1$ dB, $T^{\mathrm{m}} = 0.3$ dB; 4: $G^{\mathrm{trgt}} = 11$ dB, $T = 3$ dB, $G^{\mathrm{m}} = 11.0$ dB, $T^{\mathrm{m}} = 2.9$ dB; 5: $G^{\mathrm{trgt}} = 8$ dB, $T = 0$ dB, $G^{\mathrm{m}} = 7.9$ dB, $T^{\mathrm{m}} = 0.2$ dB; 6: $G^{\mathrm{trgt}} = 8$ dB, $T = 6$ dB, $G^{\mathrm{m}} = 8.2$ dB, $T^{\mathrm{m}} = 5.6$ dB.

It is worth to point out that, only moderate signal/pump level was considered in this work so the SSRS and PSRS processes were assumed to be independent from each other. If the signal/pump level is high, this assumption is no longer valid and the situation will be more complicate. The related study is undergoing.

In conclusion, a simple approximate linear relationship of individual pump power versus on-off gain and gain tilt in a multi-pump B-DFRA was established by numerical simulation and demonstrated experimentally on SMF with a linear correlation factor higher than 97.7%. Based on this linear relationship, a novel gain control algorithm for multi-pump B-DFRA considering SSRS effect was proposed, where only 3 constants for each pump wavelength and simple algebraic calculation were required. The constants can be pre-determined by linear regression from measured data. The simplicity of the algorithm makes it possible to be realized easily and fast by a microprocessor.

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