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Effective Automatic Gain Spectrum Adjustment of Bi-directionally Pumped Broadband Raman Amplifiers

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Abstract: An effective feedback algorithm is proposed to dynamically control the pump powers of bi-directionally pumped broadband (>70nm) Raman amplifiers. By introducing a simple saturation factor, wide-range and robust gain spectrum adjustment can be achieved.

1. Introduction

Multi-wavelength pumped Raman amplifiers (RAs) have been widely used in ultra-long haul transmission systems. To meet the practical requirements, the gain spectra of RAs should be controlled in real-time according to various system requirements. Apparently, dynamic gain spectrum control (DGSC) of RAs can be derived cost-effectively by direct adjustment of Raman pump powers. To date, several methods have been reported to realize DGSC of backward pumped RAs, which include pump grouping method [1], linear-matrix method [2], and iterative pseudo-inverse matrix method [3], etc. However, no control methods for RAs with bi-directional pumping are proposed. In this article, we demonstrate an effective feedback algorithm to achieve automatic DGSC of bi-directionally pumped broadband RAs for the first time. By introducing a simple saturation factor, wide range gain spectrum control can be derived even for a 100nm high-gain RA within 5 iterations, which will take a millisecond or so by using built-in high-speed microprocessors.

2. Theory model and control algorithm

Firstly we consider an optimized steady-state RA with N pump wavelengths and M signal channels. According to Equ.2 in ref. [2], when neglecting the high-order term, the approximate pump power vector (N×1) at Δz distance can be deduced (detailed prove will be presented in conference) as

$$\Delta\mathbf{P}_\mathbf{P}(\Delta z)=\mathbf{A}(0)\cdot\Delta\mathbf{P}_\mathbf{P}(0)+s\mathbf{B}(0)\cdot\Delta\mathbf{P}_\mathbf{P}(0)\,,\quad(1)$$

where constant s is the saturation factor, and pump powers are launched at $z=0$. $\mathbf{A}$ and $\mathbf{B}$ are both N×N matrices and assumed unchanged within Δz length, which is correct when Δz is small enough. We have

$$\mathbf{A}(0)=\begin{bmatrix} G_{P_1}(0) & 0 & \cdots & 0 \\ 0 & \ddots & \vdots & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & 0 & 0 & G_{P_N}(0) \end{bmatrix},$$

where $G_{P_N}(0)=\exp[(\sum_i g_{P_N P_i}\overline{P}_{P_N}(0,\Delta z)-\alpha_{P_N})\cdot\Delta z]$, $\overline{P}_P(0,\Delta z)$ is the average pump power form 0 to Δz, subscripts $P_1\cdots P_N$ denote different components of vector $\mathbf{P}_\mathbf{P}$, and g_{PP}, α_P are pump-pump Raman coefficient and fiber loss, respectively. While

$$\mathbf{B}(0)=\begin{bmatrix} 0 & B_{12} & \cdots & B_{1,N} \\ B_{2,1} & 0 & \cdots & \vdots \\ \vdots & \vdots & \ddots & B_{N-1,N} \\ B_{N,1} & \cdots & \cdots & 0 \end{bmatrix},$$

where

$$B_{M,N}=\frac{g_{P_M P_N}\overline{P}_{P_M}(0,\Delta z)}{C_{P_M}(0)}\cdot(G_{P_M}(0)-1)$$

and $C_{P_N}(0)=\sum_i g_{P_N P_i}\overline{P}_{P_N}(0,\Delta z)-\alpha_{P_N}$. Then we can derive approximate pump integral vector along fiber span as

$$\begin{aligned}\Delta\mathbf{I}_\mathbf{P}(z)&=\{\Delta z+[\mathbf{A}(0)+s\mathbf{B}(0)]\Delta z+\cdots\}\cdot\Delta\mathbf{P}_\mathbf{P}(0)\\&=\mathbf{H}\cdot\Delta\mathbf{P}_{\mathbf{P}in}\qquad(2)\end{aligned}$$

where $\Delta\mathbf{P}_{\mathbf{P}in}$ denotes the change of input pump powers, and $\mathbf{H}$ is the N×N control matrix. Next, applying Equ.(2) to a bi-directionally pumped RA with N_f forward and N_b backward pump wavelengths we have

$$\Delta\mathbf{P}_{\mathbf{P}f,in}=\mathbf{H}_f^{-1}\cdot\mathbf{g}_{\mathbf{SP}f}^{-1}\cdot\Delta\mathbf{G}_\mathbf{S}(z)\quad\text{and}$$

$$\Delta\mathbf{P}_{\mathbf{P}b,in}=\mathbf{H}_b^{-1}\cdot\mathbf{g}_{\mathbf{SP}b}^{-1}\cdot\Delta\mathbf{G}_\mathbf{S}(z),\qquad(3)$$

where subscript f and b denote forward and backward pumping schemes, $\Delta\mathbf{G}_\mathbf{S}$ is an M×1 vectors denoting the variations of signal gain profile (in decibel), and $\mathbf{g}_\mathbf{SP}^{-1}$ is the pseudo-inverse matrix of $\mathbf{g}_\mathbf{SP}$, which is a M×N matrix representing the pump-signal Raman coefficient. Here we assume the saturation factor is identical for both forward and backward pumps, and the Raman interactions between the forward and backward pumps are neglected. As a result we can adjust forward and backward pump powers independently. By carrying out feedback pump adjustment based on Equ.3 iteratively, wide dynamic range can be achieved with an appropriate saturation factor.

3. Simulations and results

When applied to practical systems, $\mathbf{g}_\mathbf{SP}$ can be measured experimentally, and $\Delta \mathbf{G}_{\mathbf{S}}$ can be determined through real-time detection of the gain spectra or gains of several probe channels. Moreover, the original pump power distributions $\mathbf{P}_{\mathbf{P}}(z)$ of a steady-state RA can be measured directly by using modified OTDR method [4]. It should be highlighted that saturation factor s is the key parameter of our algorithm, which can be achieved by either experiments or simulations. The principle is to find the optimal s value which can lead to the minimum difference between the target and the actually output gain profile after one iteration.

To achieve general conclusions, we consider the non-degenerate pump wavelength setup, which uses unequal forward and backward pump wavelengths, and 100km NZ-DSF is used as gain medium, while the conclusions are also valid for other fiber types. Genetic algorithm is adopted to optimize the pump powers as well as wavelengths of the steady-state RAs. Through intensive computations, we show the typical s values at different conditions in Tab.1. It can be found the broader the gain band is, the less the s value is. And s also decreases slightly as the total signal power and the fiber length increase. As shown in Fig.1, larger than 24dB dynamic range (-16~8dB net gain, which equals about 4~28dB on-off gain) can be achieved within 4 iterations by using $s = 0.4$ when Raman gain bandwidth is less than 85nm. However, when the gain band is up to 100nm, the converge speed of the algorithm will be slower if a lower gain level is required, which is mainly due to decreased pump-pump interactions. This problem can be solved by adding an accelerating factor to the longest wavelength pump. In Fig.2a, 22dB dynamic range can be obtained for a 100nm RA with 3 forward pumps (1401,1418 and 1428nm) and 5 backward pumps (1412,1458,1468,1478 and 1517nm) by using $s = 0.08$, and it can be found the relationship between output gain level and input pump powers is nonlinear as shown in Fig.2b. Moreover, tilted rather than flat gain profiles can also be obtained by using this method as shown in Fig.2c, which tells the robustness of the proposed algorithm.

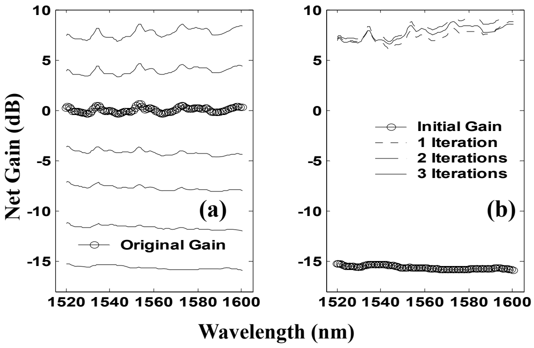

Fig.1 (a) -16~+8dB gain spectrum adjustment of a 100 channel, 80nm RA with 2 forward and 4 backward pumps, (b) the adjusting process from -16dB to 8dB. Total input signal power is 20mW.

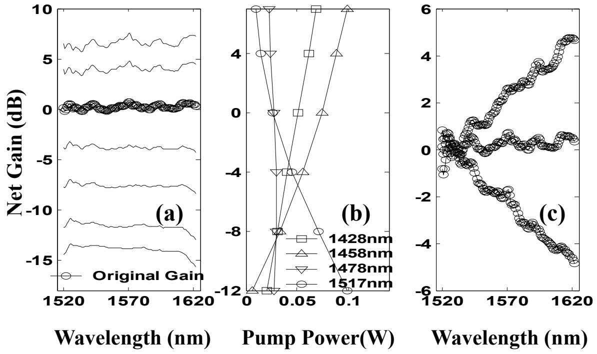

Fig.2 (a) -15~+7dB gain adjustment of a 100nm RA with 3 forward and 5 backward pumps, (b) various gain levels vs. pump powers, and (c) achieved gain profiles with negative and positive slope. Total input signal power is 50mW.

At last, it will take less than 0.3ms to complete one iteration for detecting stable gain profile. Consequently the total adjustment time will be 1ms or so for most conditions, which is enough for practical applications.

4. References

[1] Y. Emori et al., "Simple gain control method for broadband Raman amplifiers gain-flattened by multi-wavelength pumping," ECOC 2001, TuA2.2, 158-159 (2001).

[2]. W. Zhang et al., "A simple algorithm for gain spectrum adjustment of backward pumped distributed fiber Raman amplifiers," PTL **16**, 69-71 (2004).

[3]. X. Zhang et al., "Automatic real-time control for gain-flattened fiber Raman amplifiers," OC **239**, 79-84 (2004).

[4].P. Kim et al.,"In situ design method for multichannel gain of a distributed Raman amplifier with multiwave OTDR,"PTL **14**,1683-1685(2002).

Table.1 Typical s values at different conditions.

	60nm band, 2 forward and 2 backward pumps	80nm band, 2 forward and 4 backward pumps	90nm band, 2 forward and 5 backward pumps	100nm band, 3 forward and 5 backward pumps
S value	0.6	0.4	0.2	<0.1