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Few-pumped flat Raman fiber amplifier for parallel distributed FBG-based sensor system

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ABSTRACT

Multi-pump technique is frequently adopted to improve the flatness of Raman fiber amplifier (RFA), but brings the issues in terms of cost and algorithm complexity. In this article, we limit the number of pumps and the few-pumped RFA is proposed and investigated by optimizing the power and wavelengths. We further define three new factors to evaluate the improvement ratio of gain and flatness and determine the advisable number of pumps. By using the designed RFA, an experiment of distributed fiber Bragg grating-based sensor system is developed, and the flatness of less than ±0.44 dB is obtained with the gain of about 3 dB in the range of 1510–1570 nm.

1. Introduction

Raman fiber amplifier (RFA) has been received much attention and frequently reported in the application of optical sensor system due to low noise figures and flat gain spectrum [1–3]. To extend its operating bandwidth, multiwavelength pump technique is introduced into RFA, but may worsen the gain flatness because of the interactions between pumps and signals [4,5]. Aiming to improve flatness, the optimized algorithms, such as GA [6], HGA [7,8], Shooting [9], Matrix [10], DE [11], and Feed-forward [12], are deeply investigated to balance such interactions. Moreover, the larger number of pumps, in general >10, is necessary to obtain the better performance on flatness and gain, simultaneously [4].

Nevertheless, it surely leads the problems in terms of cost and algorithm complexity. In [7], the higher gain with the increase of pumps is demonstrated but at the expense of huge time-consuming, and the CPU time reaches 8157.75 s when the pump number is equal to nine. Thus, the practicability of the above schemes must be seriously considered although the opitmizations of 12 pumps and 15 pumps have been reported in [5,7], respectively. In this article, we propose a novel few-pump scheme to flatten the gain of RFA in which the number of pumps is limited less than 5. And three new factors named gain power improvment ratio (GPIR), flatness power improvement ratio (*FPIR*) and joint improvement ratio (JIR) are introduced to quantify the efficiency of pumps. We further develop the flatenss experiment in a parallel distributed sensor system with 66 fiber Bragg gratings (FBGs) by using the optimized RFA, and the flatness of less than ±0.44 dB is obtained in the range of 1510–1570 nm.

The rest of the paper is organized as follows. In Section 2, the theory model of multi-pumped RFA is studied. In Section 3, the gain flatness is evaluted under the various number, power and wavelengths of pumps. In Section 4, the joint-linear-weight method is bulit, and the suitable pump number is determined by comparing the improvement ratios of gain and flatness. In Section 5, the flatness experiments in a dirstitubed FBG-based sensor system is described with the optimized quard-pumped RFA. The conclusions are summarized in Section 6.

2. Theory model

Assuming the number of pumps and signals are n and m, respectively, wave propagation in the backward multi-pumped RFA is then described by the coupled nonliear equations[9,13]

$$\pm\frac{dP_k}{dz} = (-\alpha_k+\gamma_k)\left(P_k+P_{ASE,k}\right)+\sum_{\substack{j=1\\ j\neq k}}^{n+m} g(\nu_j,\nu_k)P_j \times(P_k+P_{ASE,k}+h\nu_k\Delta\nu F_{phon}),\quad (k=1,2,\ldots,n+m) \qquad (1)$$

where P_k, ν_k and α_k are the power, frequency, and attenuation coefficient for the kth wave (i.e., pump or signal), γ_k is Rayleigh

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backscattering coefficient, z is a variant and denots the length of gain fiber, $P_{ASE,k}$ is the forward-propagating spontaneous Raman scattering power in the channel bandwidth Δv, h is Planck's constant, and F_{phon} is a factor related to the number of optical phonons. And $g(v_j, v_k)$ is called gain coefficient which describes the power transfer by stimulated Raman scattering between *jth* and *kth* waves. From [14], in the case of Stokes ($v_j > v_k$)

$$g(v_j, v_k) = \left(\frac{1}{K_{\text{eff}}A_{\text{eff}}}\right) g_j(v_j - v_k) \tag{2}$$

and in the case of anti-Stokes ($v_k > v_j$)

$$g(v_j, v_k) = -\left(\frac{1}{K_{\text{eff}}A_{\text{eff}}}\right)\left(\frac{v_k}{v_j}\right) g_k(v_k - v_j) \tag{3}$$

where A_{eff} is the effective fiber area, and K_{eff} is the polarization factor. This model can describe the interactions of pump-to-pump, pump-to-signal, and signal-to-signal. Further, given that we take no account of the effects of Rayleigh backscattering and P_{ASE}, the net amplification factor for each signal channel could be expressed by

$$G_k = \frac{P_k(L)}{P_k(0)} = \exp\left(-\alpha_k L + \sum_{\substack{j=n+1 \\ j\neq k}}^{n+m} g(v_j, v_k) I_j\right) \exp\left(\sum_{j=1}^{n} g(v_j, v_k) I_j\right) \tag{4}$$

where $I_j = \int_0^L P_j(z)\mathrm{d}z, \quad j = 1, 2, \ldots, n+m$ is the power integrals of the pumps. The first term in the right hand of (4) shows the fiber attenuation and signal-to-signal Raman scattering, and the second term shows the gross (pump-to-signal) Raman gain in the channel k. So the key of the flattest G_k is to balance the interactions among pumps and signals by the combination of pumps with the optimized power and wavelengths. Undoubtedly, it is a complex problem to solve and the corresponding complexity of the optimal algorithms is intensively dependent to the variants, such as n, m, and L.

3. Parameters optimization of few-pumped RFA

The conventional RFA system is shown in Fig. 1 which consists of signals, multi-pumped source, gain fiber, isolators (ISO) and optical spectrum analyzer (OSA). The signals denoted by T_j, $j = 1,2,\ldots,m$, cover the whole C-band (1510–1570 nm), and the output power is the same and fixed at −3 dB. The backward-pumped configuration is adoped and one-stage 25-km single mode fiber (SMF-28) are used as the gain medium. In addition, the selected wavelength division multiplexer (WDM) and isolators have the wide pass-band for the input signals and pumps.

Further, we set $\alpha = 0.2$ and 0.22 dB/km for signals and pumps, respectively, $A_{\text{eff}} = 50 \times 10^{-12}\,\text{m}^2$, $K_{\text{eff}} = 2$, $g = 1.046 \times 10^{-13}$ m/W, $m = 7$ (the interval wavelength of signals is 10 nm), and the temperature is 300 K [15]. Additionally, the value of n is limited in the range of from 1 to 5. Then by fourth-order Rung–Kutta, the optimized power and wavelengths of pumps are gotten (see Table 1) and the corresponding gain flatness is experimentally presented in Fig. 2.

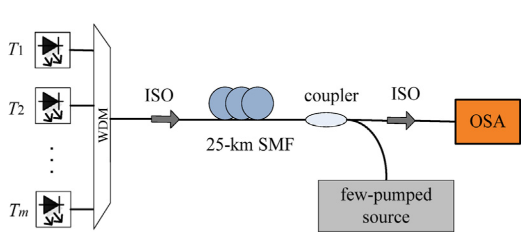

Fig. 1. Configuration of Few-pumped RFA.

Table 1
The optimized power and wavelengths of pumps.

n	Wavelength (nm)	Power (mW)
1	$\lambda_1 = 1435.2$	$P_1 = 210.7.$
2	$\lambda_1 = 1420.7,$	$P_1 = 108.2,$
	$\lambda_2 = 1445.3$	$P_2 = 127.9$
3	$\lambda_1 = 1421.9,$	$P_1 = 108.6,$
	$\lambda_2 = 1434\ .3,$	$P_2 = 136.6,$
	$\lambda_3 = 1446.8$	$P_3 = 117.3$
4	$\lambda_1 = 1410.2,$	$P_1 = 141.8$, $P_2 = 76.9,$
	$\lambda_2 = 1427.1,$	$P_3 = 81.8$, $P_4 = 160.2$
	$\lambda_3 = 1441.7,$	
	$\lambda_4 = 1454.3$	
5	$\lambda_1 = 1405.7,$	$P_1 = 108.2$, $P_2 = 93.1,$
	$\lambda_2 = 1421.2,$	$P_3 = 79.9$, $P_4 = 150.7,$
	$\lambda_3 = 1433.5,$	$P_5 = 119.6$
	$\lambda_4 = 1447.1,$	
	$\lambda_5 = 1459.3$	

Here the average gain is defined as

$$G_{\text{ave}}(n) = \frac{1}{m}\sum_{j=1}^{m} G_j \tag{5}$$

where G_j is the gain of the signal T_j. The gain flatness is then calculated by

$$\text{GF}(n) = \pm\frac{\left|G_{\max}(n) - G_{\text{ave}}(n)\right| + \left|G_{\min}(n) - G_{\text{ave}}(n)\right|}{2} \tag{6}$$

where $G_{\max}$ and $G_{\min}$ are the maximum and minimum gain, respectively. From Fig. 2, the worst gain and flatness is given when $n = 1$ and 2. By calculation based on (5) and (6), the corresponding $G_{\text{ave}}(1) = 1.5714$ dB, GF(1) = ±0.826 dB, $G_{\text{ave}}(2) = 1.711$ dB and GF(2) = ±0.58 dB, respectively. With the rise of n, we find the gain is approximately linear-enhanced and the flatness are obviously improved. For the case of $n = 5$, the average gain reaches 4.73 dB and the flatness is controlled below ±0.15 dB.

4. Evaluation based joint-linear-weight method

The above results show that the more pumps lead the better performance on gain and flatness, which is consistent with the results in [4,5,7]. However, besides the algorithm complexity, the increased cost and energy consumption reslting from pumps must be concerned. In order to quantify the benefits from the rised n, we

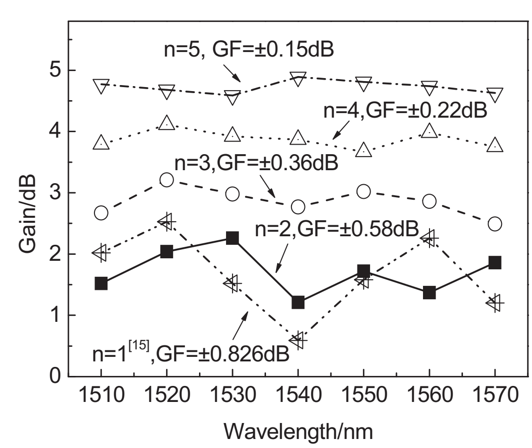

Fig. 2. Gain and flatness with the various pump number.