

Novel hybrid optimal algorithm for broad-band Raman amplifier

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Abstract: A hybrid optimal algorithm, named the SAA-PA in brief, based on the simulated annealing algorithm (SAA) and the Powell algorithm (PA) is proposed. The proposed algorithm puts the random search strategy of the SAA into the PA, which can prevent optimizing courses from trapping in local optima. The SAA-PA can effectively solve multimodal optimization in the distributed multi-pump Raman amplifier (DMRA). Optimal results show that, under the conditions of the on-off gain of 10 dB, the gain bandwidth of larger than 80 nm and the fiber length of 80 km, the gain ripple of less than 1.25 dB can be designed from the DMRA with only four backward pumps after the optimization of the proposed SAA-PA. Compared with the pure SAA, the SAA-PA can attain a lower gain ripple with the same number of pumps. Also, the relationship between the optimal signal bandwidth and the number of pumps can be simulated numerically with the SAA-PA.

Key words: distributed multi-pump Raman amplifier; simulated annealing algorithm; Powell algorithm

Wavelength-division-multiplexing (WDM) based on fiber amplifiers provides a transmission platform for the optical fiber communication systems and networks. Because the gain bandwidth of the erbium doped fiber amplifier (EDFA) is much narrower than the low loss window of standard optical communication fibers, there is growing interest in broadband flat-gain optical fiber amplifiers to exploit more of the available fiber bandwidth and increase the capacity of WDM systems. Gain bandwidths in excess of 10 THz (approximately 80 nm) have been demonstrated using either hybrid fiber amplifiers or fiber Raman amplifiers pumped with multiple wavelengths. However, all of these amplifiers, especially those with larger bandwidths, have offered a drawback of poor gain flatness^[1–2]. In the case of the Raman amplifier with multiple pumps, by appropriately choosing wavelengths and powers of pump waves, it can provide broad amplification bandwidth and flexible center wavelength compared with the pure EDFA. The distributed multi-pump Raman amplifier (DMRA) can also make the noise characteristics significantly improve, long transmission distances be realized and existing systems be upgraded. Additionally, the DMRA can mitigate fiber nonlinear effects, and improved the optimal signal-noise-ratio (OSNR) without the need to increase the input optical signal power.

In principle, the DMRA can obtain an arbitrary gain spectra by the proper choice of pump wavelengths and powers. However, the main difficulty is that inter-

actions of pump-to-pump, signal-to-signal and pump-to-signal make the system highly nonlinear, and even a direct problem of finding the gain profile, for a given input pump distribution, becomes somewhat complicated. Therefore, the DMRA design presents a grand challenge to numerical optimization. It involves multiple powers and wavelengths.

Recently, several methods have become available to select the appropriate wavelengths and powers in the DMRA, but their results are hard to classify as optimization. Perlin and Winful employed the genetic algorithm (GA) to optimize the gain-flatness and gain-bandwidth performance and the optimal results are exciting, but their methods may be trapped in local optima of the search space due to the intrinsic weakness of the traditional GA^[3–4]. In Ref. [5], the SAA was employed to optimize the Raman-gain spectrum; however, their convergent speed and precision are rather low because of the inherent shortcomings of the SAA. Another neural network method was introduced in Ref. [6], but it only partly obtained the optimization in pump power excluding wavelengths. In this paper, we present a hybrid SAA-PA for optimizing the DMRA design. The novel hybrid algorithm puts the random research strategy of the SAA into the PA, so it can effectively prevent the optimizing course from trapping a local minimum and can obtain a global minimum. The optimal results of flatness and bandwidth are compared with the pure SAA. These results are helpful in the real design of the DMRA.

In this paper, a hybrid algorithm based on the simulated annealing algorithm and the Powell algorithm for the optimization of the Raman amplifier gain pro-

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file is proposed. The proposed method is compared with the pure simulated annealing algorithm. Simulation results show that it is a fast and effective numerical method, which can be applied to real system performance design. The numerical results also exhibit the relationship between the gain bandwidth and the number of backward pumps.

1 Mathematical Model

In the bandwidth design for distributed multi-pump Raman amplifiers, noise effects such as spontaneous Raman scattering, Rayleigh backscattering and thermal factors are ignored in general, since the power of backscattering pumps and signals is lower by about 30 dB and 20 dB than their original power, and the power of forward and backward noise is less than that of input signals by about 30 dB^[2]. Thus the major influences are the interactions of pump-to-pump, signal-to-signal and pump-to-signal, as well as the fiber attenuation, in simulating the amplifier gain profile. In the steady state, their coupled equation can be described as^[3-6]

$$\begin{aligned} \pm \frac{dP_k}{dz} = & -\alpha_k P_k + \sum_{j=1}^{k-1} \frac{g_{\nu_j}(\nu_j - \nu_k)}{K_{\text{eff}} A_{\text{eff}}} P_j P_k - \\ & \sum_{j=k+1}^{m+n} \frac{\nu_k}{\nu_j} \frac{g_{\nu_k}(\nu_k - \nu_j)}{K_{\text{eff}} A_{\text{eff}}} P_j P_k \quad k=1, 2, \dots, n+m \end{aligned} \quad (1)$$

where P_k , ν_k , and α_k are the power, the frequency and the attenuation coefficient for the k -th wave, respectively; $A_{\text{eff}} = 2$, which is the effective area of optical fiber; the factor of $K_{\text{eff}} = 2$, which accounts for polarization randomization effects. This is because spontaneous emission and thermal noise are not correlated with signal. Although the signal is polarized, the states of polarization (SOP) of signal and noise are scrambled and mixed together in the process of propagating through the optical fiber^[7]. $g_{jk} = g_{\nu_j}(\nu_j - \nu_k)$ is the Raman gain coefficient from wave j to k . The frequency ratio ν_k/ν_j describes vibrational losses. The minus and plus signed on the left side describe the backward-propagating pump waves and forward-propagating signal waves, respectively. The frequencies ν_k are numerated in the decreasing order of frequency ($i = 1, 2, \dots, m+n$). The terms from $j = 1$ to $j = k-1$ and from $j = k+1$ to $j = m+n$ cause amplification and attenuation of the channel at frequency ν_k .

2 Hybrid Optimal Algorithm

Gain flattening is a key issue in broadband optical amplifier design. For the DMRA, the gain flatness is dependent on the number of the used pump wave-

lengths and the pump power distribution. In order to get better simulation results, some improvements on the objective function have been taken based on Ref. [5]. Considering that the pump power and wavelengths should be constrained in a specific area, the optimization of the DMRA is actually a problem with some constraints. Given that the initial configuration is definite "an internal point", we adopt the internal penalty function method in the objective function. Therefore, the optimization becomes unconstraint.

$$\text{ripple}(x, \gamma) = \frac{1}{G_{\text{expected}}} \cdot \sqrt{\frac{1}{N} \sum_{i=1}^N G_{\text{expected}} - G_i(x)}^2 + \gamma \sum_{i=1}^m \frac{-1}{g_i(x)} \quad (2)$$

where G_{expected} , γ , N , m , G_i express the required optical gain, the penalty factor, the number of the signal light, the number of the constraints, and the optical gain of the i -th signal, respectively. Note that G_i is a function of the pump frequencies ν and the input pump powers P . $g_i(x)$ ($j = 1, 2, \dots, m$) is the i -th constraint inequation of the pump powers and wavelengths. It is easily seen that the best gain flatness is obtained when ripple (x, γ) takes the global optima. The main procedure of the proposed internal penalty function method is given as follows:

- ① Set an initial penalty factor $\gamma_1 > 0$, a reduction coefficient c , $0 < c < 1$, a precision $\varepsilon > 0$, and a generation number $k = 1$. Generate a set of pump powers and wavelengths satisfying constraints, $x^{(0)} \in D$.
- ② Start from $x^{(k-1)}$, calculate the global minimum of ripple (x, γ_k) , suppose that it is $x^{(k)}(\gamma_k)$.
- ③ If the terminating criteria, $\beta_k = \gamma_k \sum_{i=1}^m \frac{-1}{g_i(x^{(k)})} < \varepsilon$ is satisfied, then stop and output optimal results, else go to ④.

- ④ Set $\gamma_{k+1} = c\gamma_k$, $k = k+1$ and go to ②.

The SAA is based on the analogy between the simulation of the annealing of solids and the problem of solving large combinatorial optimization problems. The PA is a general purpose algorithm for solving optimization problems in the finite-dimensional space. Both methods have their advantages and disadvantages. In order to combine the advantages of both, one uses the PA to find the local optimal, and then employs the SAA for finding out the better value so as to escape from local minima. Therefore, if these two kinds of searches cooperate properly, the hybrid optimization algorithm will have good properties. The outline of the SAA-PA is shown as follows^[8]:

- ① Initialize the parameters. Randomly generate an initial state as the current state.
- ② Use the PA to get the local optima.

③ Starting from the result of the PA, employ the random search of the SAA for finding a better state. If the better state can be found in the pre-set number of iterations, then the PA continues to optimize. If the better state cannot be found in the pre-set number of iterations, the local optima can be regarded as the global optima. In the loop iterations, the temperature of the SAA decreases all the time. The percentage of obtaining the better state is getting lower and lower as the temperature drops. Therefore, the pre-set number should be a little larger so as to find the global optima.

In Ref. [9], an experiment was proposed to introduce a simple gain control method by adjusting the launched pump powers. In our simulation we take the same parameters as in the experiment. Numerical results from our mathematical model have a very good accordance with the experimental results.

3 Optimal Results and Discussion

In the numerical calculations of Eq. (1), we employ the fast four-step method^[10] and assume that $A_{\text{eff}} = 80 \times 10^{-12} \text{ m}^2$, $K_{\text{eff}} = 2$, $L = 80 \text{ km}$, $\alpha = 0.2 \text{ dB/km}$ for signals and pumps. There are 100 signal channels spaced by 1.2 nm/channel , and the power of each

channel is 0 dBm . The criterion of optimized bandwidth in simulation is that the on-off gain and the relative gain flatness are required to be about 10 dB and less than 0.15 in four backward-propagating pumps, respectively. In the stage of initialization, we first define the range of every pump wavelength and power, which consists of a fixed range. Secondly, we formulate an objective function according to every penalty term. The initial configuration must be in the defined range so as to apply the internal penalty function.

The optimized results are demonstrated in Fig. 1, which exhibits a comparison of the signal bandwidth and gain ripple between the optimizations of the proposed hybrid SAA-PA and the pure SAA. The optimized parameters are given in Tab. 1, where the two schemes correspond to the two gain profiles in Fig. 1. Tab. 1 and Fig. 1 illustrate that the results obtained from the SAA-PA are much better than those obtained from the pure SAA. It is easily found that, both gain bandwidths have exceeded 80 nm . The gain ripple of the SAA-PA is below 1.25 dB , while the simulation result of the SAA is beyond 2 dB . Furthermore, the number of the objective functions called by the SAA-PA is much lower than by the SAA, so the hybrid method is much faster.

Tab. 1 Optimal results of two methods

Optimal method	Function call	Pump power P_j/mW				Wavelength λ_j/nm				$\Delta\lambda/\text{nm}$
		P_1	P_2	P_3	P_4	λ_1	λ_2	λ_3	λ_4	
SAA	1 956	181.50	192.10	85.20	89.40	1 414.48	1 433.32	1 458.21	1 489.16	85.30
SAA-PA	1 237	152.24	129.10	89.95	28.95	1 421.61	1 435.19	1 453.18	1 484.04	82.40

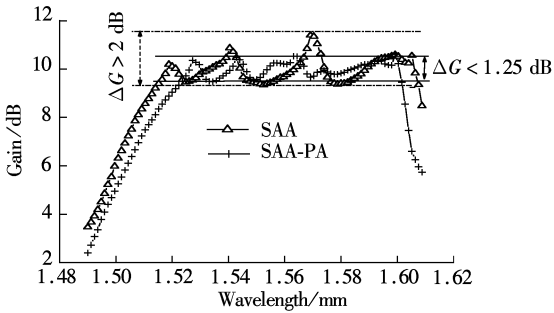


Fig. 1 Optimal gain spectrum of the SAA-PA and the SAA

To more clearly understand the relationship between pumps and signals, the evolution of all channels transmitting along the fiber is plotted in Fig. 2 and Fig. 3. It is easily found that there are strong interactions of pump-to-pump, signal-to-signal, and pump-to-signal (the pump-to-signal interaction makes signal increase when $z \geq 60 \text{ km}$). Fig. 3 shows that, at first, the fiber attenuation dominates, but the Raman gain dominates continuously in the latter. The shorter wave-

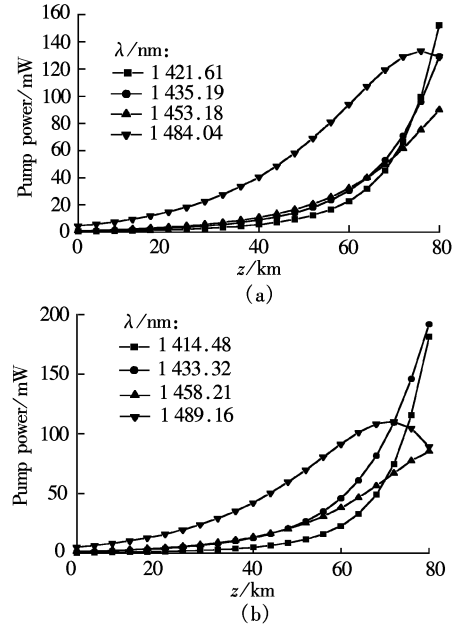


Fig. 2 Evolution of pump powers along the transmission fiber. (a) Optimal results of the SAA-PA; (b) Optimal results of the SAA

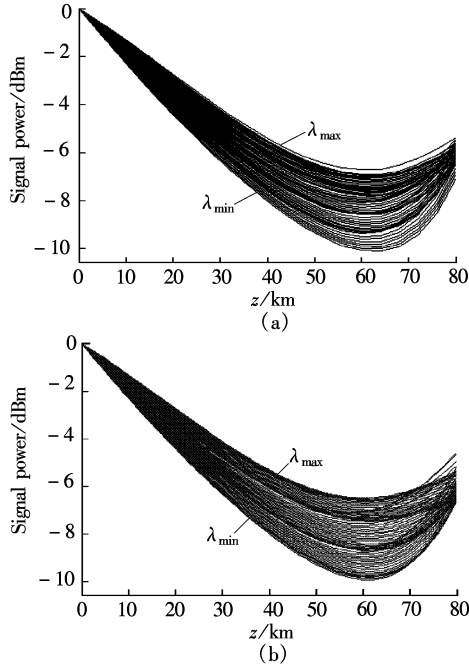


Fig. 3 Evolution of signal powers along the transmission fiber. (a) Optimal results of the SAA-PA; (b) Optimal results of the SAA

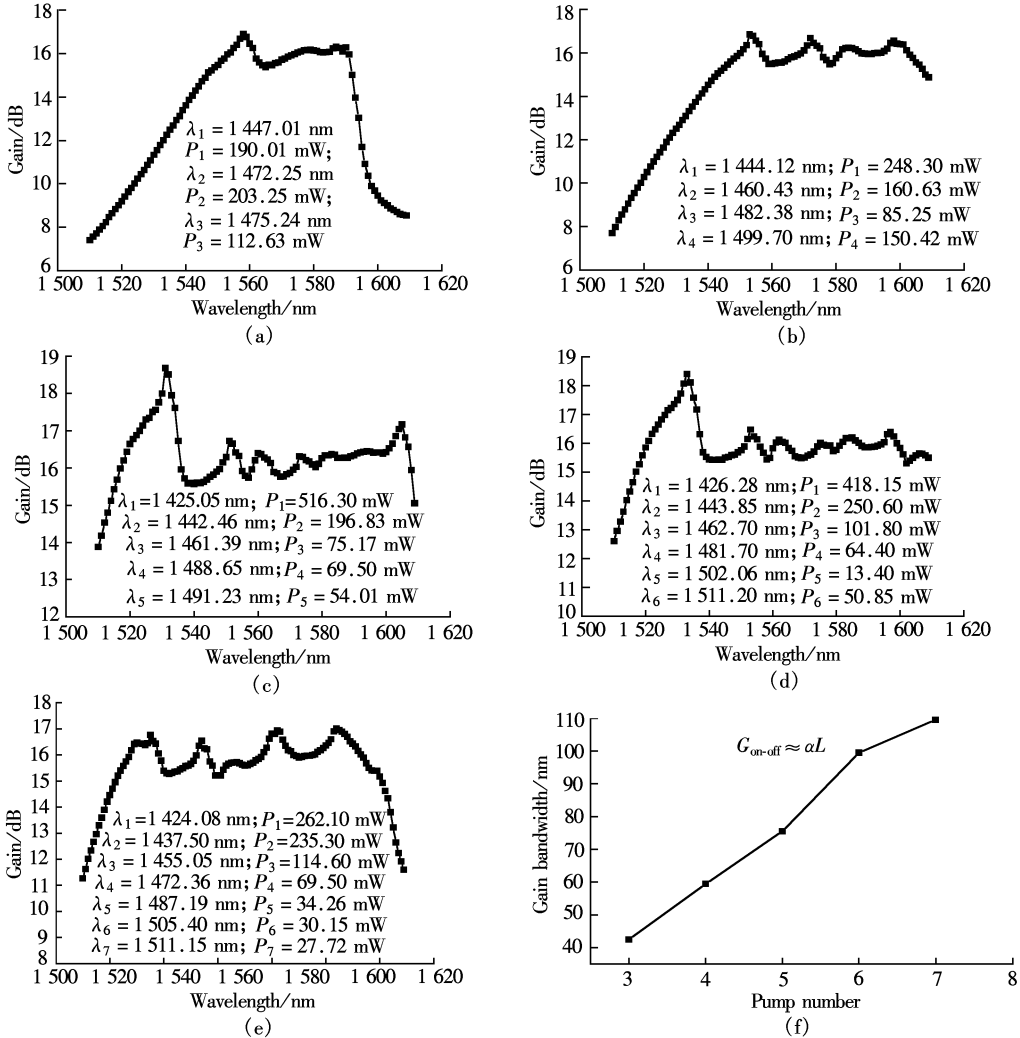


Fig. 4 Optimal gain profile with different numbers of pumps. (a) For three pumps; (b) For four pumps; (c) For five pumps; (d) For six pumps; (e) For seven pumps; (f) Relationship between gain bandwidth and pump number

length signals decrease more quickly than longer wavelength signals do when $z \leq 60 \text{ km}$. The reasons are that stimulated Raman scattering (SRS) makes the power of higher frequency waves flow into that of lower frequency waves.

Fig. 4 shows the relationship between gain bandwidth and the number of backward pumps, where the on-off gain is assumed as 16 dB so as to compensate for the attenuation of signals. In each figure, the optimal pump wavelengths and powers are demonstrated. In the numerical calculations, the wavelength of center channel is given as 1570 nm. From Fig. 4, we can see that when the on-off gain are approximately the same, the maximum gain bandwidth increases with the addition of pump number, i. e., the optimal bandwidth $\Delta\lambda$ are 42.5, 59.51, 75.50, 99.50, and 109.50 nm for three, four, five, six, and seven pumps, respectively. In general, the proposed hybrid optimization method can availably find the better combination of backward pumps and decrease the computing time.

4 Conclusion

This paper presents a new optimization approach SAA-PA based on proper integration of the SAA and the PA for solving gain spectra of the DMRA. The SAA-PA combines the advantages of the SAA and the PA together. The SAA-PA can not only escape from local minima easily, but also converge to global optima rapidly. In addition, the internal penalty function method is applied to the objective function of the DMRA. It turns the optimization from constrained to unconstrained. The optimal results show that the bandwidth of more than 80 nm can be realized from the DMRA with only four pumps in our design conditions of the on-off gain of about 10 dB, the gain ripple of less than 1.25 dB and the fiber length of 80 km. The gain ripple drops from more than 2 dB to below 1.25 dB compared with the pure SAA. Simulation results also show that the optimal signal bandwidth $\Delta\lambda$ can be evidently broadened by means of increasing the number of pumps. The SAA-PA is an efficient and convenient algorithm to be applied in multimodal optimizations.

References

- [1] Radic S, Chandrasekhar S, Bernasconi P, et al. Feasibility of hybrid Raman/EDFA amplification in bidirectional optical transmission [J]. *IEEE Photon Technol Lett*, 2002, **14** (2): 221 – 223.
- [2] Liu Xueming, Lee Byoung-ho. Optimal design of fiber Raman amplifier based on hybrid genetic algorithm [J]. *IEEE Photon Technol Lett*, 2004, **16**(2): 428 – 430.
- [3] Perlin Victor E, Winful Herbert G. Optimal design of flat-gain wide-band fiber Raman amplifiers [J]. *IEEE J Light-wave Technol*, 2002, **20**(2): 250 – 254.
- [4] Zhou Xiang, Lu Chao, Shum Ping, et al. A simplified model and optimal design of a multiwavelength backward-pumped fiber Raman amplifier [J]. *IEEE Photon Technol Lett*, 2001, **13**(9): 945 – 947.
- [5] Yan Minhui, Chen Jianping, Jiang Wenning, et al. Automatic design scheme for optical-fiber Raman amplifiers backward pumped with multiple laser diode pumps [J]. *IEEE Photon Technol Lett*, 2001, **13**(9): 948 – 950.
- [6] Xiao P C, Zeng Q J, Huang J, et al. A new optimal algorithm for multipump sources of distributed fiber Raman amplifier [J]. *IEEE Photon Technol Lett*, 2003, **15**(2): 206 – 208.
- [7] Shu Namiki, Yoshihiro Emori. Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelength-division-multiplexed high-power laser diodes [J]. *IEEE J Select Topics Quantum Electron*, 2001, **7**(1): 3 – 16.
- [8] Zhao Yuqing, Yu Zhijun. Speeding up global optimization method-combined method of Powell method with simulated annealing method [J]. *Acta Electronica Sinica*, 1998, **26**(9): 75 – 77. (in Chinese)
- [9] Yoshihiro Emori, Soko Kado, Shu Namiki. Simple gain control method for broadband Raman amplifiers gain-flattened by multi-wavelength pumping [A]. In: *European Conference on Optical Communication* [C]. Amsterdam, Holland, 2001. 158 – 159.
- [10] Liu Xueming, Zhang Hanyi, Guo Yili. A novel method for Raman amplifier propagation equations [J]. *IEEE Photon Technol Lett*, 2003, **15**(3): 392 – 394.

一种新的宽带拉曼放大器的混合优化算法

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摘要: 基于模拟退火算法(SAA)和鲍威尔算法(PA)提出了一种新的混合优化算法——模拟退火鲍威尔算法(SAA-PA). 该算法将模拟退火算法的随机搜索策略纳入到鲍威尔优化算法中, 能使优化解不陷入局部最优从而获得全局优化解. 该优化方法可以有效地解决多目标的优化问题, 特别适用于拥有多个局部最优值的分布式多泵浦拉曼放大器(DMRA)的优化问题. 仿真结果显示, 在 80 km 传输光纤上只要 4 个后向泵浦就能实现开关增益 10 dB, 带宽大于 80 nm, 增益平坦度小于 1.25 dB 的平坦增益. 与单纯的模拟退火算法的优化结果相比, 在相同数目的泵浦条件下所得优化结果的增益谱特性有了显著的提高. 同时, 该方法可以较方便地仿真出信号增益带宽与泵浦数目的内在关系.

关键词: 分布式多泵浦拉曼放大器; 模拟退火算法; 鲍威尔算法

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