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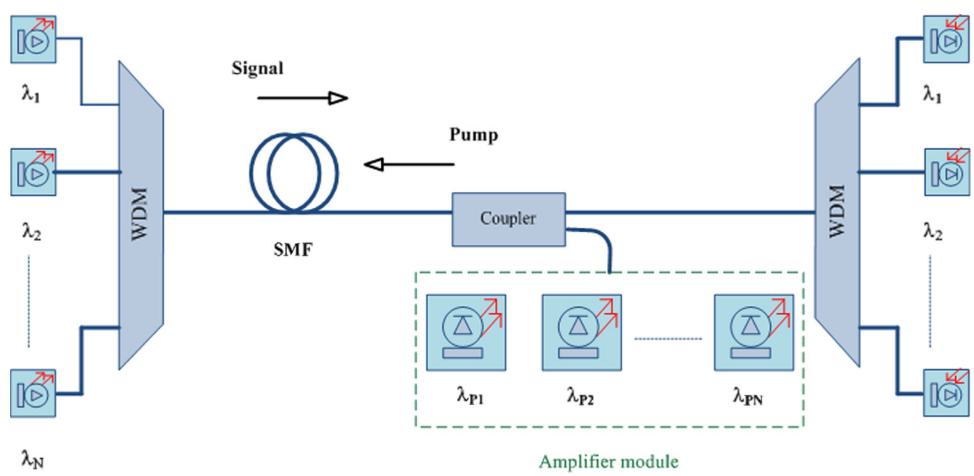


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# Optimization of Distributed Raman Amplifiers Using a Hybrid Genetic Algorithm With Geometric Compensation Technique

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**Abstract:** This paper proposes an accurate method that combines a hybrid genetic algorithm (GA) with a geometric compensation technique applied to an analytical Raman amplifier model to obtain the optimal design of multipump distributed Raman amplifiers. The geometric compensation enables partial determination of the GA initial population and works as a refinement in the search of the best possible solutions. We develop a self-contained algorithm that is capable of meeting on–off gain and ripple specifications to broadband Raman amplifiers, without the need for a previous study of the search space. As a result, we determine wavelengths and powers using the minimum number of pump lasers necessary to meet the given specifications. Our method has shown to be robust in the simultaneous analysis of multiple parameters and multiple objective problem. The processing time required to design large bandwidth Raman amplifier is minimized when compared with that obtained by a standard GA.

**Index Terms:** Raman amplifier design, optical amplifiers, optimization, Raman scattering.

## 1. Introduction

Supported by the developments in laser technologies, Raman amplifiers became one of the most renewed research subjects. The advantages of its use, such as improved noise figure, larger bandwidth, the possibility of a flat gain and the possibility of employing a Raman amplifier in an already installed fiber [1], [2] are some of the reasons that lead to this revived interest. The increase in bandwidth of the optical networks also helped to revive this interest since the Raman amplifier can be modeled to work in larger bands such as the C plus L bands.

Despite the advantages presented by Raman amplifiers, there are some difficulties in their implementation. The task of arranging the design parameters, such as the number of pumps and its wavelength and power to achieve a flat gain, proved to be a real challenge, due to their nonlinear characteristics and the fact that the mutual interactions between pumps and signals are described by a set of coupled nonlinear differential equations [3], [4]. Another important impairment is that Raman amplifiers tend to cost around 10 times more than erbium-doped fiber amplifiers (EDFAs), which makes the definition of its parameters an important task as well as the minimization of the numbers of pumps needed to reach specific levels of gain and ripple.

The design of Raman amplifiers can be classified as a multiple objective problem, since it requires the optimization of the on–off gain, the gain ripple, the number of laser pumps, and the amplifier cost. In such a way, it is common to make use of global search mechanisms to perform this task. To overcome this problem, several optimization methods capable of simultaneously determining the wavelengths and powers of Raman pump lasers have been proposed, such as neural networks [5], simulated annealing [6], a semianalytical model [7], and the genetic algorithm (GA) [8], [9].

Our method using hybrid GA (HGA) with geometric compensation technique (GCT) is a useful strong tool to design distributed or concentrated Raman amplifiers applied in practical wavelength division multiplexing (WDM) systems. The first need of such amplifiers is determining the number and specifications of the Raman pump lasers, such pump power and pump wavelength, that characterize a multiple objective problem.

Xiao *et al.* [5] have developed an optimal-configuration algorithm for multipump sources considering pump powers and the gains of their peak-gain wavelengths, respectively, as the input and output variables of single-layer feedforward neural networks [5]. Nevertheless, the focus is not optimizing the gain ripple or speeding up the computational time for Raman amplifier design. An extend algorithm based on the fundamentals of simulated annealing presented by Yan *et al.* [6] discussed the optimization of multipump configuration and proposed a new method to arrange the pump wavelengths and powers in backward-pumping scheme. However, the gain ripple and processing time are still issues to be addressed with such a method. Zhou *et al.* have reported a semianalytical model by considering multiple wavelength pumps and signals and the interactions among them under triangle Raman profile approximation [7], but in this case, the pump interactions are numerically solved using the Runge–Kutta method, which means a time costly process. An example of GA applied to the Raman amplifier design optimization can be found in [8], where Neto *et al.* developed a method that combines the GA with the Nelder–Mead method in order to obtain the gain optimization of distributed Raman amplifiers (DRAs). Liu *et al.* presented an HGA based on the clustering fitness sharing and the elite replacement of population applied in the optimization of the signal bandwidth in Raman amplifiers [9]. However, the computation time is still a matter in such methods.

In this paper, a method based on an HGA is proposed to determine the wavelength and power of a set of laser pumps used in a DRA system. Our main goal is to improve the efficiency of the GA metaheuristic, with no expense of accuracy. It has been accomplished by developing an algorithm capable of finding a configuration with minimum number of pumps needed in order to attend to some basic project needs, such as signal band, maximum on–off gain, and minimum ripple (set as 1 dB), with no need for a previous study of the search space and with no loss in efficiency. The most important differences are that, the majority of GAs applied to the DRA problem has a single objective, either gain or the gain ripple, while this paper proposes a method to simultaneously optimize gain and gain ripple. A GCT is considered to find a combination of Raman gain curves in order to obtain flat gain over a desired target bandwidth. Therefore, the GCT improves the GA performance. An analytical Raman model developed in [10] has been used to perform the gain and ripple computation. The main advantage of the analytical method is that it can speed up the design optimization of Raman amplifiers. Another important feature is the robustness of the hybrid algorithm, which is able of optimizing the DRA, independent of its initial parameters, with no need for rearrangement of the fitness function.

This paper is organized as follows: Raman CW model analysis is presented in Section 2, the optimization methods are described in Section 3, the results and comparisons are displayed in Section 4, and Section 5 contains the conclusions.

## 2. Raman Simulation Models

The DRA can present different configurations according to the pump scheme, i.e., forward-pump, backward-pump or bidirectional. Several improved features, especially in the gain values and noise figure, are observed in the Raman amplifier performance, depending on the pump configuration choice.

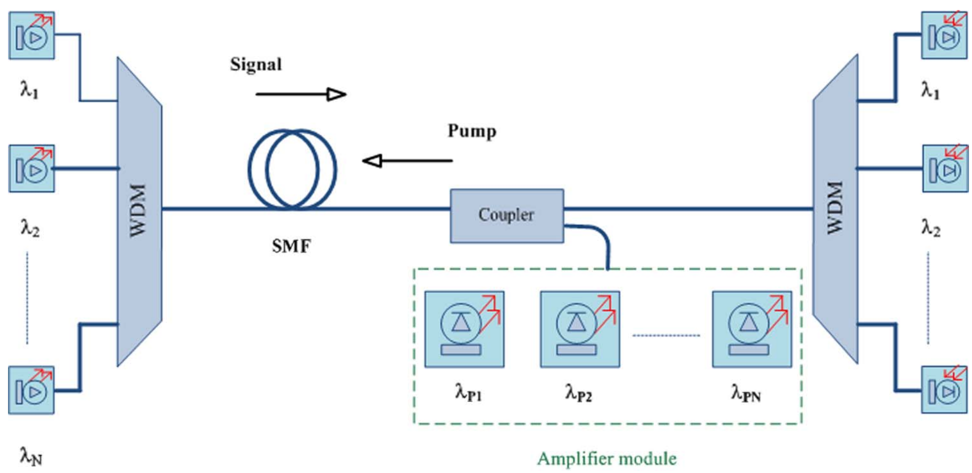


Fig. 1. Proposed DRA backward-pumped configuration.

In this paper, we have studied a backward-pump DRA used in a WDM transmission system, as shown in Fig. 1. In general, the backward-pump configuration can guarantee a better quality of the amplified signal when compared with the forward-pump configuration, particularly with regarding the following factors: Relative Intensity Noise transfer noise from pump lasers, polarization dependence of gain, and nonlinear effects in the amplifier fiber [2]. A pump module containing multiple pump lasers is coupled with the transmission fiber in order to propagate in the opposite direction of the input channels. It is important to mention that wavelengths and powers selection of these multiple pump lasers is critical to obtain a flat gain. Any minor changes in their values can impose a major increase to the gain flatness [11].

The main approaches to simulate optical signal propagation in Raman amplifiers use numerical or analytical formulations that consider steady-state solutions. Numerical modeling of time-dependent propagation involves the solution of the nonlinear Schrödinger equations, which govern the power interaction between pump and signal powers [12]–[14].

In the steady-state analysis, both numerical and analytical approaches can be applied with quite good accuracy. A complete numerical method enables the inclusion of effects such as pump depletion, wavelength dependence of pump and signal loss, amplified spontaneous emission (ASE), and double Rayleigh scattering (DRS). However, the solution is a very time consuming process.

A good example of analytical solution is reported in [10], which can be applied to the steady-state analysis. Even though the analytical approach neglects some effects or only partially computes them, it allows an accurate calculation of gain and ripple within substantially reduced computing time.

This paper reports the analyzes of a wide range of pump lasers combination using an HGA with a GCT and the analytical model described in [10]. The presented method allows us to find the best possible gain and ripple response. Due to the reduced time required from the analytical model reported in [10] to solve the coupled equations, it has been chosen to optimize the Raman pumps wavelengths and powers used in the HGA + GCT proposed in this paper. The number of Raman pump lasers is also an optimization parameter since it means cost reduction that can become an issue for most practical purposes.

Specifically, the analytical approach considers pump-to-pump and signal-to-pump interactions and takes into account wavelength-dependent effects such as effective area spectral dependence and individual signal loss coefficients. Nevertheless, neglects the pump depletion by the signal, the wavelength dependence of the pump loss, and disregards noise effects, since the gain calculation is not significantly affected by this approximation [10], [12]. A more detailed explanation on the analytical solution and its constraints can be found in our previous work [10].

## 3. Optimization Algorithm

A multiple objective optimization problem [15] may be defined as a process in which a group of objective parameters are optimized simultaneously. However, these variables have performance criteria that are often in conflict with each other. Therefore, in such cases, the term optimization is applied as the act of finding a solution, which results are acceptable values, according to some decision standards, to all objective variables.

According to the previous definition of multiobjective optimization problem (MOP), the issue of optimizing the configuration of DRAs regarding their gain and ripple responses can be defined as an MOP, once the objectives of achieving a specified value for gain and ripple, which are the propositions of this paper, fall into the characteristics of conflicting parameters.

As many MOPs, the search space of the Raman optimization problem is multimodal and irregular, which makes it is difficult to find deterministic algorithms capable of solving it. As a result of this difficulty, deterministic techniques of optimization are usually unable to find good solutions, which are represented in our case by configurations with gain above and ripple below the specified project parameters. Therefore, to solve MOPs, it is more common to use more complex algorithms that are related to heuristic methods defined in the stochastic techniques of optimization.

This paper will focus on the area of Evolutionary Algorithms (EAs) [16] and, more specifically in the subarea of GAs [17]. We propose an HGA to solve the problem of determining the minimum number of pumps so that meets the project specifications of maximum on–off gain and minimum ripple to a Raman amplifier working in a bandwidth larger than the C band. The algorithm is based on the functions of a GA, such as mutation, crossover, and reproduction. However, the determination of the initial family is partially limited to pumps located in specific wavelength areas determined by a method of geometric compensation.

### *3.1. HGA*

GAs are search and optimization algorithms that involve numerical solution, inspired by the natural processes of natural selection and genetics. The main characteristics of a standard GA are the generation of a random initial population, the processes of selection, crossover, mutation, and elitism. However, probably the most important feature of the GAs is the fitness function, because it is what defines the quality of each individual solution [17].

In the HGA proposed in this study a couple of changes are applied to the standard GA described above, as illustrated in Fig. 2. The HGA is initially set with two pumps in order to search for a solution to the required on–off gain, ripple, bandwidth, and fiber length. Afterwards, an initial population of 200 individuals is created, where 75% is defined randomly in a bandwidth between 130 nm and 30 nm below the smallest signal wavelength, and the other 25% is determined by the GCT, since it provides the best tradeoff between processing time and optimized amplifier performance. These two values (75% of random and 25% of HGA) were obtained after running the optimization algorithm for many different initial seeds. The initial population has been also calculated without HGA, with 50%, 75%, and 100% as well. Best results, i.e., higher gain and ripple lower than 1 dB, were always obtained to 25% of HGA. After applying the HGA method, the algorithm will perform the standard GA functions throughout 100 generations.

The fitness functions are the same for both GA and HGA methods. We have used the standard procedure for multiobjective optimization, i.e., a linear combination between both objectives, i.e., gain and ripple.

If the required values of gain, ripple and bandwidth are not reached, the procedure for two pumps is repeated up to three times. This is due to the probabilistic characteristics of the GA, which does not guarantee that a good initial population will always be formed, even with the use of geometric compensation. After the third time, if the premises are not reached, the number of pumps is increased by 1, and the procedure restarts.

As can be seen in Fig. 2, the maximum number of pumps allowed for the system to search through is 5. This limit is imposed due to the high cost of laser pumps for Raman amplifiers, which tends to be a limiting factor for a real project. Since the main goal of this paper is to find appropriate

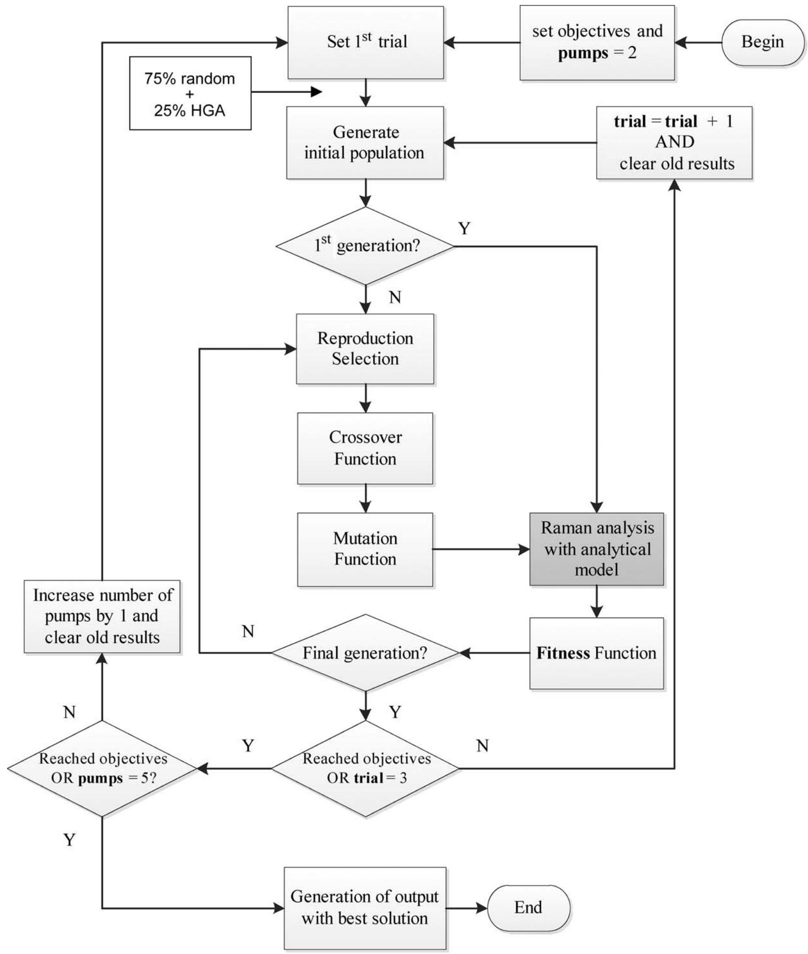


Fig. 2. Diagram of HGA applied to the DRA optimization.

solutions for the design of Raman amplifiers, the limiting number of five pumps was set in order to keep the solutions within a reasonable cost range.

### 3.2. GCT

The GCT is based on an algorithm of nonlinear regression that consists of finding a linear combination of Raman gain curves in order to generate a flat gain over a desired target bandwidth. To generate an approximated curve to represent the Raman gain coefficient GR for silica fibers as a function of the frequency shift, an expression is proposed by [11]

$$G_R(\delta f) = \sum_{i=1}^{m} a_i e^{-\left[\frac{(\delta f + f_i)}{\Delta f_i}\right]} \tag{1}$$

according to (1), the $G_R$ curve is obtained by a sum of Gaussian functions, where $a_i$, $f_i$, and $\Delta f_i$ are, respectively, the normalized amplitude, the central frequency, and the width of the $i$th Gaussian curve. It is important to notice that the frequency shift $f$ is negative due to its calculation being made as the difference between signal and pump frequencies. To fit the Raman gain curve, it is necessary to use nine Gaussian curves. The parameters necessary to reproduce the silica Raman gain curve are described in [11].

In order to achieve a flat gain over a large spectrum, it becomes necessary to make use of several pumps. In this method, the pump wavelength peak gain determination is based on the sum of the Raman gain curves adjusted as Gaussian curves. The desired DRA gain curve $G_{DRA}(f)$ is then obtained by fitting the sum of the curves to a flat unitary line over the entire gain bandwidth considered for amplification. The equation for the DRA gain is given by

$$G_{\mathrm{DRA}}(f) = \sum_{j=1}^{n} A_j G_R\left(f - f_j^p\right) \tag{2}$$

where $f$ is the frequency of the signals, and $A_j$ and $f_j^p$ are the amplitude related to the power integral, which is represented by a number between 0 and 1, and the frequency of the $j$th pump, respectively. In the sum, $n$ represents the number of pumps used to amplify the desired bandwidth and must be provided along with the bandwidth itself before starting the fitting.

The method used to fit the DRA gain considers a nonlinear least-square method based on a trust-region-reflective algorithm. The input of the method is the desired bandwidth and the number of pumps that should be used. An initial random position for the pumps is generated, and then, the method is applied in order to determine the position and the amplitude that will generate the most linear combination as output.

Regarding the GCT, the main issue to be addressed is the technique does not consider the interactions between signals and pumps and, therefore, does not indicate the exact wavelength to place the pumps in order to achieve the maximum gain with minimum ripple. However, it gives a reasonably good idea for where to place them in order to maintain low ripple.

## 4. Numerical Results

In order to test our HGA to be used in the design of DRAs, we have defined the input parameters, such as the number of pumps, their wavelengths and powers, the DRA bandwidth, and the fitness function as well. The fitness function has been defined as a function of the average on–off gain and the ripple.

Our goal was to maximize the gain while keeping the ripple smaller than 1 dB. However, any extension in the amplifier bandwidth, for instance the C and C+L band, requires additional pump lasers to maintain a flat gain response. As Raman pumps impact the cost of the amplifier, when compared with those used in EDFAs, the maximum number of pump lasers is also an optimization parameter and should be kept to a minimum. Therefore, it is extremely important to determine the best Raman amplifier configuration set with the minimum number of pumps to attend practical applications.

We have started our analysis studying the HGA convergence. Table 1 illustrates the parameters used in the simulations, and Fig. 3 shows the algorithm convergence. This analysis is important to demonstrate the effectiveness of the algorithm, showing that in few generations, the population converges to a specific region of the search space. As one can see in Fig. 3(c), in about 80 generations, the population has already converged to the region around high gain and with ripple bellow 1 dB. It takes about 13 min. for the HGA to determine the on–off gain for a five-pump configuration in an ordinary PC with 2 GB of RAM.

We also have performed some comparisons between the standard GA and the proposed HGA. Table 2 shows the results obtained for both methods as a function of the expected gain of 2, 4, 6, and 9 dB and ripple smaller than 1 dB over the C+L band. We have decided to use different number of pumps for each expected gain.

Table 2 illustrates the advantages of the HGA over the standard GA method. As one can see, for small gain values, the GA shows better results since the search space is small. However, as the expected gain increases, the HGA proves to have a higher efficiency, since the GCT improves the quality of the initial population and, therefore, makes it easier to find a good solution. As it can be seen in Tables 1 and 2, not only the HGA is capable of generating better solutions in a single procedure, which is faster than a regular GA could. It is the case to four-, six-, and nine-pump lasers.

TABLE 1

Parameters used in convergence study of the HGA

| Parameter | Value |
|---|---|
| Fiber length [km] | 100 |
| Fiber type | SMF-28 |
| Number of pumps | 5 |
| Maximum total pump power [mW] | 1500 |
| DRA bandwidth | C band |
| Fitness function | Maximum on-off gain, ripple ≤ 1.0 dB |
| Population | 200 individuals |
| Crossover probability | 70 % |
| Mutation probability | 8.3 % |
| Elitism | Best individual only |
| GCT percentage | 25 % |

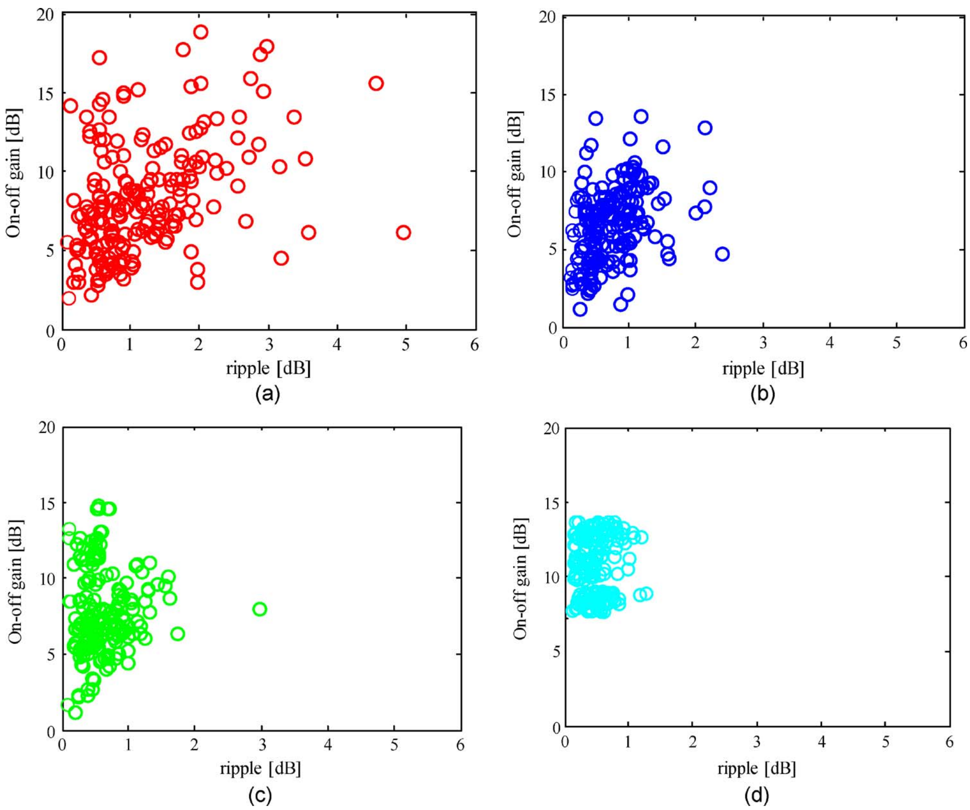


Fig. 3. Convergence of the HGA obtained for 5 pump lasers after (a) one, (b) 40, (c) 80, and (d) 100 generation(s).

Fig. 4 shows the on–off gain versus signal wavelength over the entire C+L band for the cases illustrated in Table 2. The full symbols represent HGA and the empty symbols represent the standard GA. As one can see, the HGA method gets better results as the expected gain increases.

Finally, we have used the HGA method to study the influence of the number of pumps in the amplifier gain considering two situations: the extended C band (1530 to 1600 nm) and (b) the entire

TABLE 2

Comparison between the GA and HGA in terms of gain results, number of pump lasers, and elapsed time given in seconds

| Expected Gain [dB] | GA | | | HGA (GCT percentage of 25 %) | | |
|---|---|---|---|---|---|---|
| | Pumps | Gain [dB] | CPU Time [s] | Pumps | Gain [dB] | CPU Time [s] |
| 2 | 2 | 2.06 | 4.65 | 2 | 2.78 | 32.40 |
| 4 | 4 | 4.03 | 991.32 | 4 | 4.08 | 563.09 |
| 6 | 6 | 6.36 | 6,808.86 | 6 | 6.61 | 3,964.80 |
| 9 | 9 | Unable to find a solution only in 3 trials | | 9 | 9.75 | 8,157.75 |

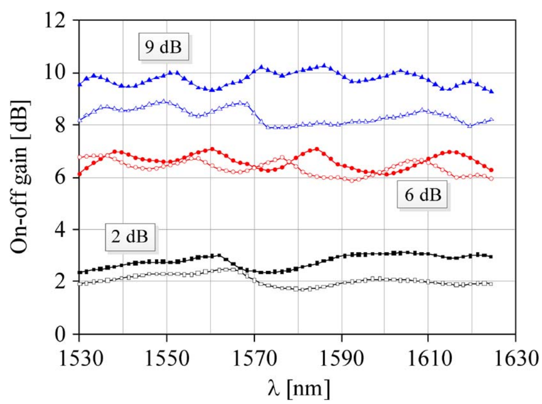


Fig. 4. On–off gain versus signal wavelength for the standard GA (empty symbols) and for the HGA (full symbols) with GCT of 25%.

C+L band. For this study, we have used the parameters previously presented in Table 1. Fig. 5 shows the on–off gain versus the number of pumps obtained after running ten different cases. We have stopped the simulations after 100 generations. As we can see, for the extended C band, the increase of pumps achieves a maximum at around 11 pumps, whereas the full band continues to increase up to the 15th pump. The maximum power limitation imposes that the maximum power of each pump diminishes as the pump number increases. A larger bandwidth allows for a better distribution of a higher number of pumps, and this way, the limitation of power is not as critical as in a relatively smaller bandwidth, where the lower individuals pump power become a limit to the gain. The interpolations of the calculated curves allowed obtaining smother curves, where bars in Fig. 5 indicate the error.

## 5. Conclusion

We have presented in this paper an accurate method that combines an HGA with a GCT applied to the design of multipump DRAs. The HGA method has proven to be robust to refine the search of wavelengths and powers of pump lasers required to the best configuration of Raman amplifiers. It would best fit the requirements of a practical amplifier design, since it allows the designer to determine the wavelength and powers which combined generate the necessary on–off gain and ripple with the smallest number of pump lasers as possible. The importance of this analysis is mainly due to the cost of components required to set up DRAs in comparison with EDFAs.

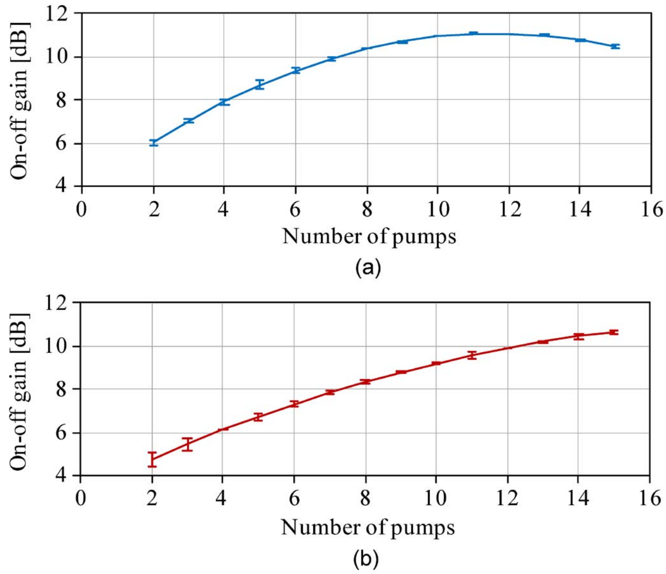


Fig. 5. On–off gain as a function of the number of pump lasers. (a) Extended C band (1530 to 1600 nm) and (b) the entire C+L band.

Another important feature of the HGA is its ability to determine good answers in extended bandwidths, keeping the ripple below 1 dB, which is an important need for the functionality of optical receivers. The possibility to use the whole extension of both the C and L bands allow the system to improve its capacity enormously, being of great interest for optical networks companies. Therefore, the HGA is a robust computational method which is capable of determining high-quality solutions for the project of Raman amplifiers based on different project standards such as fiber length, signal bandwidth, as well as on–off gain and ripple, allowing the project's cost to be reduced significantly.

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