

Automated optimization tools help to design gain flattened broadband Raman amplifiers

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Fiber Raman amplifiers in WDM systems have recently received much more attention because of their greatly extended bandwidth and distributed amplification with the installed fiber as gain medium [1], [2]. It has been shown that the bandwidth of the amplifier can be further increased and gain spectrum can be tailored by using pumping with multiple wavelengths [1]-[9].

Several strategies are proposed for static gain flattening. Wide-band amplifier gain spectrums have been demonstrated using either a hybrid fiber amplifier consisting EDFAs, lumped Raman amplifiers, and a gain-equalizer [10], or fiber Raman amplifiers pumped at multiple wavelengths [6], [9], [11]. At the device level, optical amplifiers come in a variety of configurations: backward-, forward-, and bi-directionally pumped, discrete or distributed, single- or multi-stage [1], [2].

One of the main difficulties of designing a multi-pumped Raman amplifier is that pump-to-pump and signal-to-signal Raman interactions make the system highly nonlinear, thereby complicating the design process and requiring a high number of iterations. Optical communication design tools can be utilized to determine the proper pump configuration to get optimum gain flatness. However, most of the optical communication design tools provide a simple optimization option based on parameter sweeps. Using such an option for optimization requires a manual investigation of the results, a large number of iterations, and a great deal of simulation time. A generic automated optimization tool could greatly simplify this process by eliminating user interaction and unnecessary simulations. An automatic optimization tool would examine current simulation results, compare them to the design goals, and then adjust the parameters to reach the defined design goals. Sophisticated optimization technologies are available that can minimize the required number of simulation runs, however, there is a risk of winding up with a local optimum. Therefore, the optimization procedure should be customized to a specific application. Furthermore, the parameter range and behavior of the component or system can be utilized as constraints to the optimizer. For example, Optiwave has developed a generic and flexible optimization tool as a part of its OptiSystem and OptiAmplifier⁺ packages based on a customized version of Matlab's* widely accepted and well-proven optimization procedures. This tool provides powerful multi-parameter, multi-target optimization procedures, including minimization, maximization, goal attainment, least square, and gain flattening. The minimization and maximization procedures minimize or maximize a single result by manipulating multiple parameters. Goal attainment attempts to achieve multiple result goals by changing multiple user-defined parameters. The least

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square procedure minimizes the sum of squares of multiple results by altering multiple parameters. The gain flattening procedure is used to optimize the parameters of amplifiers, filters, and pumps for the best gain flatness. It can also force several user-defined constraints on selected parameters.

A schematic of an automated gain flattening tool is shown in Figure 1. The optimization tool attempts to reach a target gain for each channel, and at the same time tries to keep the gain flatness under a given value. The ultimate goal is to achieve a certain gain for all channels and keep the gain flatness at a reasonable value. This goal is achieved by using an optimization procedure, dependent on the designer's selection, that either adjusts the amplifier parameters, the pump parameters, or both. For each set of parameters, the modified version of the design is simulated, and results are evaluated. For example, the measuring device can be a dual port WDM analyzer or an internal analyzer of Raman amplifier model.

The optimization of the Raman amplifier by using a multi-pump configuration is a complicated and time consuming procedure, given that the required pump power for a certain Raman gain is affected by several factors, including Raman gain coefficient, polarization effect, fiber length, fiber loss at pump wavelength, pump depletion, and pump-to-pump Raman interaction. From the numerical standpoint, the large number of channels further complicates the problem in the system, and the fact that interaction between every pair of the channels needs to be taken into account. Therefore, it is crucial to input accurate estimated initial values, *especially for pump wavelengths*, into the optimizer. For example, a general guideline to estimate the pump channel locations is outlined in [2]. It is based on the fact that the gain profile of a multi-wavelength pumped Raman amplifier can be expressed as a logarithmic superposition of the gain profiles caused by respective pumping wavelengths (with the assumption that magnitude of Raman gain is only determined by the corresponding pump power and wavelength). Even though this is not correct, it will provide a rough estimate for the pump channel locations. Unless it is beyond the limit, the predicted gain profile is sure to be realized by an appropriate pump power level. When an accurate estimation is provided, the optimization procedure can find the optimum pump powers and wavelengths by adjusting the pump powers and refining the pump wavelengths. In a majority of cases, optimizing only the pump powers may give sufficient gain flatness. It may also be useful to provide an extra constraint to the optimizer. For example, putting min/max constraints on the total pump power will ensure that the achieved gain is close to the required gain. Otherwise, the optimization may result in a set of optimum parameters that generates an acceptable level of flatness but a lower average gain.

As illustrative examples, we show two gain flattening designs with backward multi-pumped Raman amplifier configuration. The first one shows the optimization of pump powers and wavelengths, and the second one shows the optimization of pump powers for given wavelength allocations. Even though several pumping schemes are possible [2], we have chosen these examples because they enable direct comparison with readily available theoretical and experimental results. The technical details of the Raman amplifier model used in the simulations are provided in [12]. We included the following

effects in our simulations: attenuation, Rayleigh backscattering gain, stimulated Raman scattering (SRS) gain, spontaneous Raman scattering gain, and pump depletion in SRS.

Our first design contains 64 channels between 1512 and 1562.4 nm with 0.8 nm separations. The average power of each channel is -20 dBm. The fiber used as the gain medium is a 25 km fiber with $9.5e-014$ m/W peak Raman gain coefficient. The effective area of the fiber is 55 micron square. The loss of the fiber is 0.2 dB/km. Target amplifier forward gain is 10.0 dB. Initial wavelengths and powers of four CW pumps used for backward pumping are given in Table 1. For comparison, the initial parameters chosen are as in [5].

Table 1: Initial pump wavelength and power allocation

Wavelength (nm)	Power (mW)
1405.0	110.0
1415.0	140.0
1435.0	170.0
1460.0	140.0

With this initial pump allocation, we observed a gain flatness, defined as $10\log(G_{\max}/G_{\min})$, of 3.8 dB. The initial gain spectrum of the amplifier is shown in Figure 2.

We then applied the gain flattening optimization procedure to optimize the pump powers and wavelengths. We bound the pump powers between 0 and 300 mW [13] and we specified a gain flatness, lower than 2.1 dB. As an extra constraint, we limited the total pump power between 800 mW and 1000 mW. This is necessary to make sure that we can get a gain as high as required and force the optimizer to find a global optimum not a local one.

Optimum pump powers and wavelengths are obtained after 81 calculations. Pump power and wavelength allocation after the optimization are shown in Table 2.

Table 2: Optimum pump wavelength and power allocation

Wavelength (nm)	Power (mW)
1408.6	169.8
1419.9	204.1
1433.1	228.0
1473.4	198.0

Figure 2 shows the resulting amplifier gain in this case. The achieved gain flatness in [5] was ~ 2.6 dB. We achieved a better gain flatness than this value. After the optimization, the achieved forward gain flatness is 2 dB, maximum forward on/off gain is 15 dB, maximum forward gain is ~ 9 dB, and the forward effective noise figure flatness is 1.6 dB.

As a second example we show the optimization of pump powers in the design of a gain-flattened Raman amplifier by using a 12-wavelength-channel WDM LD unit. We then compare our results with the experimental findings of [9].

The optimized design contains channels between 1528 and 1620 nm with 4 nm separations. The average power of each channel is 0 dBm. The fiber used as the gain medium is a 25 km SMF fiber with $9.9e-014$ m/W peak Raman gain coefficient. A 12 wavelength-channel WDM high power pump LD unit is used for backward pumping. The spacing in the short wavelength section (*Pump I*) (1405 - 1457.5 nm) is 7.5 nm (~ 1 THz) while that in the long wavelength section (*Pump II*) (1465 - 1510 nm) is 15 nm (~ 2 THz) as in [9].

The initial pump powers are selected to be 140 mW for the first 4 pumps and 80 mW for the remaining. The pump powers are bound to be between 20 mW and 160 mW.

With this initial pump configuration, the observed gain flatness was 1.2 dB. The target gain provided to optimizer was 2.0 dB. As a constraint, we specified a gain flatness of less than 1.5 dB.

The optimization tool reaches the optimum pump powers after 45 calculations. Pump power allocation after the optimization is shown in Figure 3. Note the similar trend of pump power allocation with the experimental findings of [9].

For this case, the optimized forward gain of the amplifier is shown in Figure 4. Gain flatness achieved in [9] was ~ 1 dB (± 0.5 dB). We achieved better gain flatness in comparison. After the optimization, the achieved forward gain flatness is 0.73 dB, the maximum forward on/off gain is 8.8 dB, the maximum forward gain is 3.02 dB, and the forward effective noise figure flatness is 2.1 dB.

To investigate the inter-channel effect of multi-wavelength pumps, we first removed second group of pumps (*Pump II*) (last three pumps) and then removed the first group of pumps (*Pump I*) (first nine pumps), leaving *Pump II* active. The results are shown in Figure 4 for comparison. The gain flatness in the first case is 8.6 dB, and in the second case is 2.7 dB. This figure is comparable to Figure 4 of [9]. It shows that pump at 1495 nm absorbs energy from the other pumps, resulting in much more gain at 1600 nm than just the sum of each gain in the respective cases of *Pump I* and *Pump II*.

We have shown that automated optimization tools can greatly reduce the design time and required work, resulting in enhanced Raman amplifier performance. We provided the design of a wide-band gain flattened Raman amplifier with backward multi-pump configuration as an illustrative example, and compared our findings with theoretical and experimental results that exist in literature. The application of developed automated optimization tools is not limited to backward multi-pump Raman amplifiers. It can also be used to optimize any type of amplifier or design configuration.

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