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Simple design method for gain-flattened three-pump Raman amplifiers

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Abstract We propose a simple and efficient approach to the design of 3-wavelength backward-pumped Raman amplifiers with increased gain flatness over a wide spectral band. Three different methods dealing with the optimization of one or two different simple parameters are studied. Various examples are provided for illustration, and the dependence of both amplifier gain and gain flatness with pump power is shown. Gain flatness in the spectral range of 1,520–1,595 nm of about 1 dB for a 7.5 dB gain and of 1.8 dB for a 13.5 dB gain is demonstrated using only three pumps with wavelengths within the 1,420–1,480 nm interval.

Keywords Optical fibre communications · Broadband Raman amplification · Gain flattening · Raman amplifier optimization

1 Introduction

The use of multi-wavelength-pump silica-fiber Raman amplifiers makes it possible to provide a broad gain bandwidth with a good spectral uniformity (Namiki and Emori 2001). As an example, the amplifying system described in (Namiki and Emori 2001) uses 12-wavelength pumps in a 1412.5–1504.5-nm band and provides gain flatness ~0.1 dB over the wavelength range of the C + L-bands (1,527–1,607 nm) with a counter-propagating pump configuration, using 25-km of dispersion-shifted fibre as the amplification medium. Note, however, that gain flatness of about 1 dB over the spectral range of C + L-bands is quite acceptable for some applications of Raman amplifiers, such as, for example, in single-span repeaterless

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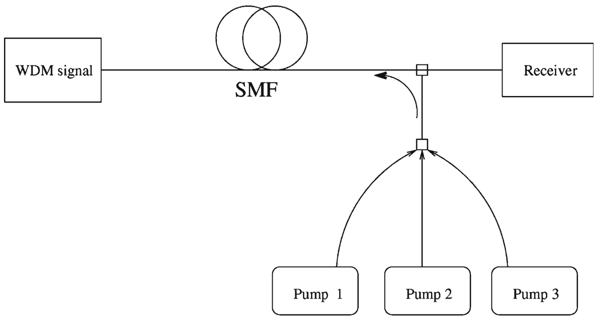


Fig. 1 Schematic depiction of the system

transmission or as part of hybrid EDFA/Raman amplified systems with independent gain equalisation. In general, when designing a Raman amplification scheme there must be a trade-off between advanced device characteristics and overall cost and practicality. A small number of pumps reduces the complexity and cost of the system, which is useful in applications such as the mentioned above, while at the same time offering potential upgrade routes for increased flatness, should the need arise, through techniques such as nonlinear pump broadening (Ellingham et al. 2005).

The implementation of multi-wavelength-pumped Raman amplification in practical transmission links requires a reliable and efficient method to adjust pump powers and wavelengths in order to obtain the desired gain profile. Although various numerical optimisation methods have already been proposed (Yan et al. 2001, Perlin and Winful 2002, Muktoyuk et al. 2004, Liu and Li 2004, Hu et al. 2004) each with their specific advantages and limitations, development of new approaches is of interest to address the variety of applications and practical boundary conditions and constraints.

In this work we introduce a simple and efficient approach to the optimal design of 3-wavelength backward-pumped Raman amplifiers. Applying this method, we demonstrate Raman amplifier gain flattening over a wide band, by choosing either an appropriate power or wavelength distribution for a three-wavelength pumping source (3λ-PS) in the 1,420–1,480-nm band, or a combination of both.

2 Proposed method and numerical model

A schematic depiction of the 3λ-pumped system is shown in Fig. 1. The full numerical model of the Raman amplifier applied in our simulations includes all of the most important physical effects affecting the Raman gain (Kidorf et al. 1999, Min et al. 2000, Namiki and Emori 2001): stimulated and spontaneous Raman scattering and their temperature dependences, Rayleigh scattering, arbitrary interactions between the pumps and the signal from both directions (signal–signal, pump–pump and signal–pump interactions) and high-order Stokes generation. Under this description, the spatial variation of the average power of a particular spectral component at frequency ν is given by:

$$\frac{dP_\nu^\pm}{dz} = \pm\Bigg\{ -\alpha_\nu^{eff}(z)P_\nu^\pm(z) + \varepsilon_\nu P_\nu^\mp(z)$$
$$+ 2h\nu\Delta\nu \sum_{\mu>\nu} \frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^+(z)+P_\mu^-(z)\right)\left(1+\frac{1}{e^{\frac{h(\mu-\nu)}{kT}}-1}\right)\Bigg\}$$

where the effective attenuation coefficient α_ν^{eff} has been defined as

$$\alpha_\nu^{eff}(z) = \alpha_\nu - \sum_{\mu>\nu} \frac{g_{\mu\nu}}{A_\mu} \left(P_\mu^+(z) + P_\mu^-(z)\right) + \sum_{\mu<\nu} \frac{\nu}{\mu} \frac{g_{\nu\mu}}{A_\nu} \left(P_\mu^+(z) + P_\mu^-(z)\right)$$
$$+ 4h\nu \sum_{\mu<\nu} \frac{g_{\nu\mu}}{A_\nu} \left(1 + \frac{1}{e^{\frac{h(\mu-\nu)}{kT}} - 1}\right) \Delta\mu$$

and α_ν is the fibre attenuation coefficient at frequency ν, $g_{\nu\mu}$ denotes the Raman gain coefficient from the component at frequency ν to the component at frequency μ, A_μ is the effective area of the fibre at frequency μ, h is Plank's constant, k is Boltzmann's constant, T is temperature, ε_ν is the Rayleigh backscattering coefficient of the fibre and $\Delta\nu = \Delta\mu$ and is the unit cell for the numerical discretisation of the frequency space and z is the spatial coordinate.

As a measure of the gain ripples we use the absolute variation of the gain over the amplification bandwidth, $\Delta G = (G_{\max} - G_{\min})$. To demonstrate our method, we consider implementations of a WDM system with 1-nm separated channels, and consider 40 channels within 1,522–1,562 nm and 75 channels within 1,520–1,595 nm, with −10 dBm/channel average power propagating through 25-km of standard single-mode fibre (SMF). We consider a three-wavelength pumping source (3λ-PS) with pumps in the 1,420–1,480 nm band, and different total pump powers depending on the gain we intend to achieve. For the simplest approach to system optimisation, we consider two basic configurations for the multi-wavelength amplifier:

(a) three pumps equally spaced in wavelength within a defined band (1,420, 1,450 and 1,480 nm), with the powers of their individual spectral components variable, and;

(b) three pumps with equal power outputs, with the wavelength of the middle component being variable.

Thus, gain flattening is performed by optimising the lower and higher wavelength pump power ratio in configuration (a), and by adjusting the middle pump wavelength in configuration (b).

There are two main applications for a Raman amplifier, namely distributed and discrete (point) amplification. In the first case, typically, the overall loss/gain balance should be equalized to zero, while in the second case the amplifying medium is required to produce an overall gain at the fiber output. In this paper, we focus on flattening the gain ripples of a discrete module capable of producing an output gain of up to 12 dB, but the proposed simple method is generic and can be applied in a variety of scenarios, including the case of distributed amplification.

In configuration (a), we have defined the relation between the powers of the lower and higher wavelength pumps by the non-dimensional parameter $k_1 = (P_1 - P_3)/(P_1 + P_3)$. In the examples shown below, the power of the central pump is set to a 60% of the total pump power. This decision is partially forced by the fixed wavelength of the pumps, and the necessity of using the central pump for direct amplification in the central region of the spectrum, while the two outer pumps are balanced in order to try to extend the amplification bandwidth. Different power ratios for the middle pump can be tried depending on the compromise between amplification bandwidth and gain requirements.

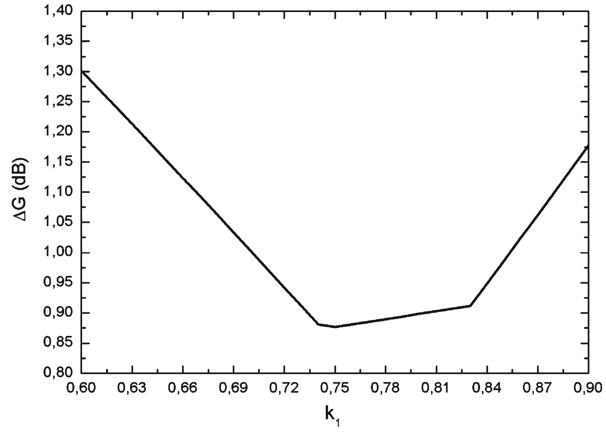


Fig. 2 Dependence of the gain flatness ΔG on the optimisation parameter k_1 for a total pump power of 500 mW

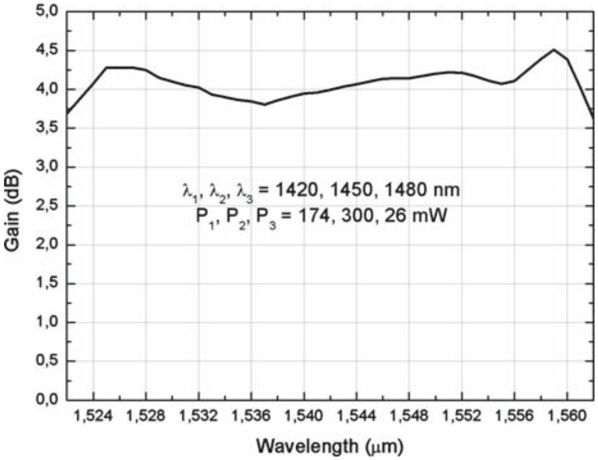


Fig. 3 Flattest amplifier gain obtained by adjusting parameter k_1 for a total pump power of 500 mW

3 Results

Once the middle pump power is fixed, the minimisation of ΔG is used as the criterion for the optimisation.The dependence of ΔG on the optimisation parameter k_1 for a total pump power of 500 mW is shown in Fig. 2. It may be seen that a clear minimum for the amplitude of the gain ripples exists at about $k_1 = 0.74$, corresponding to $P_1 = 174$ mW and $P_3 = 26$ mW. The gain contour for this best case is shown in Fig. 3. The gain difference between ripples in the optimised amplifier is lower than 0.78 dB for a 40 nm bandwidth, with an average value of the gain is about 4.0 dB (9.0 dB on-off gain). The performance shows a fast decay for broader bandwidths, in part due to the choice of a high power for the middle pump. As total pump power is increased, pump-to-pump interaction becomes stronger, and the optimal k_1 shifts towards higher values. For a total pump power of 1 W (Figs. 4, 5), the maximum gain flatness of 1.05 dB in the same 40 nm bandwidth is achieved for a k_1 of 0.955, corresponding to $P_1 = 391$ mW, $P_2 = 600$ mW and $P_3 = 9$ mW.

In configuration (b), we opt for an equal split of the pump powers, in order to increase the operational bandwidth of the amplifier, but we use variable wavelength for the middle pump. The lowest and highest wavelength pumps, each providing 1/3 of the total power, are fixed at

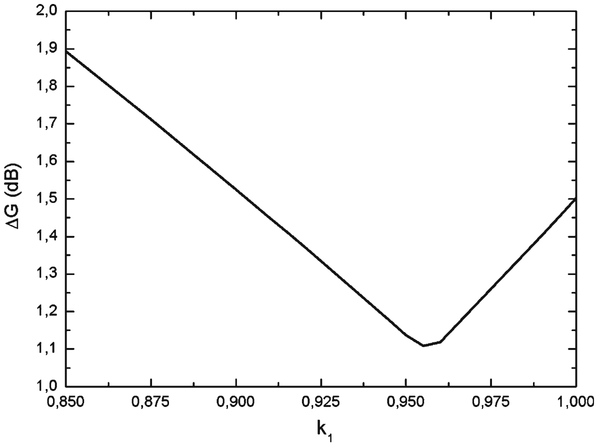


Fig. 4 Dependence of the gain flatness ΔG on the optimisation parameter k_1 for a total pump power of 1,000 mW

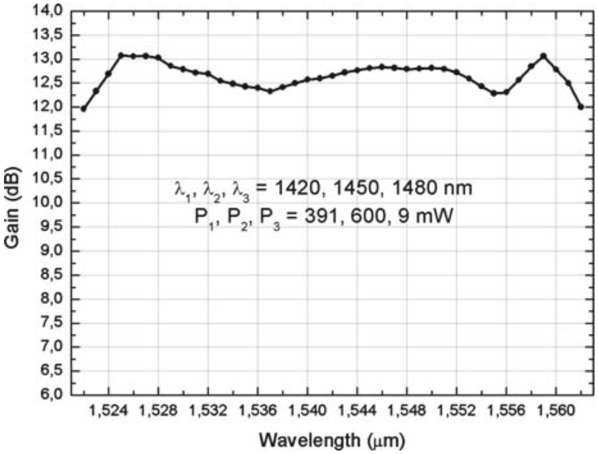


Fig. 5 Flattest amplifier gain obtained by adjusting parameter k_1 (ratio between powers in the external pumps) for a total pump power of 1,000 mW

1,420 and 1,480 nm, respectively; the spectral location of the middle pump, λ_2, is the subject of subsequent optimisation. The non-dimensional parameter $k_2 = (\lambda_2 - \lambda_1)/(\lambda_3 - \lambda_1)$, where $\lambda_{1,2,3}$ are the wavelengths of the corresponding pumps ($\lambda_3 > \lambda_2 > \lambda_1$), was used in this optimisation to track the changes on the pump wavelength. Once again, the criterion for the optimisation is the minimisation of parametre ΔG.

The dependence of ΔG on parameter k_2 is shown in Fig. 6. As it occurred in the previous case, ΔG has a clear minimum, in this case at about $k_2 = 0.34$, corresponding to a wavelength $\lambda_2 = 1440.25$ nm for the middle pump. These method provides a stable gain profile over a much broader bandwidth, with ripples < 1.05 dB over a 75 nm spectral range with an average gain of 2.5 dB (on-off gain 7.5 dB), as shown in Fig. 7.

After analyzing both methods independently, we studied their combined application, by varying k_1 and k_2 simultaneously, with 1/3 of the total power in the middle pump. A fast algorithm based on the downhill simplex method was used to find the pair (k_1, k_2) that minimized ΔG, with a result of $k_1 = 0.006$ and $k_2 = 0.33$, which is extremely close to the result obtained by the optimization of k_2 alone, and provides only a marginal improvement of the flatness, with ripples <1.03 dB.

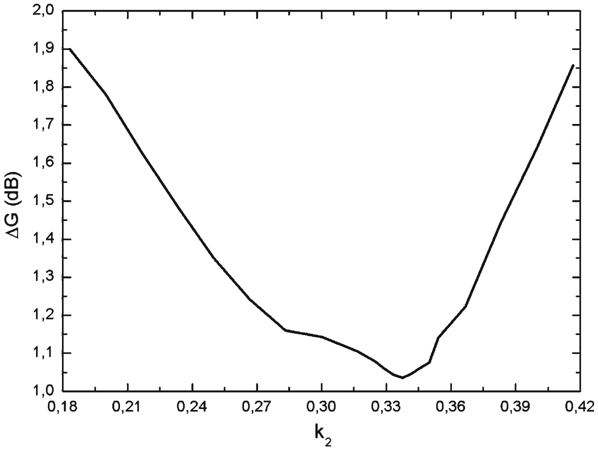


Fig. 6 Dependence of the gain flatness ΔG on parameter k_2 (spectral position of the central pump), for a total pump power of 500 mW

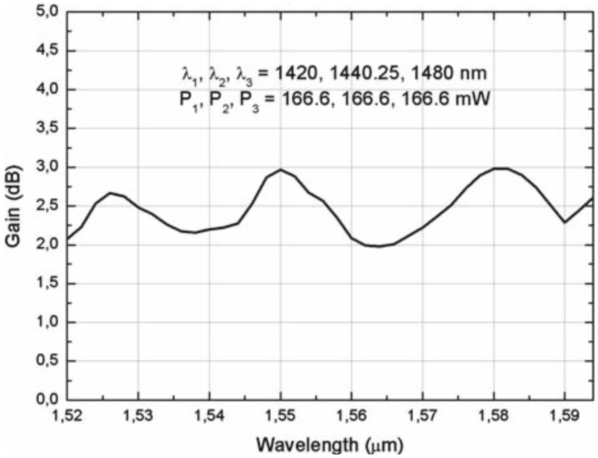


Fig. 7 Optical gain contour for the optimal position of the middle pump, with a total pump power of 500 mW

The similar performance of both methods can be traced down to the limited pump interaction when using a total pump power of 500 mW, and the benefits of using a combined approach are much more apparent when using higher pump powers.

In the case of using a total pump power of 1 W over the same amplification bandwidth of 75 nm and still with 1/3 of the total pump power in the middle pump, k_2 optimization yields an optimal gain flatness of about 3.9 dB with an average gain of about 8.5 dB (13.5 dB on-off), whereas the combined method allows us to obtain gain ripples < 1.8 dB with a similar average gain. This optimal case, depicted in Fig. 8, is reached for $k_1 = 0.27$ (corresponding to $P_1 = 422$ mW, $P_2 = 333$ mW and $P_3 = 245$ mW) and $k_2 = 0.33$ ($\lambda_2 = 1440.84$ nm).

In order for the combined method to be applicable in a variety of real systems, it has to be scalable. Figure shows the variation of the average gain and the gain flatness for an optimised system versus the total pump power. Both show a linear growth, although the faster increase of the average gain implies that the ratio between ΔG and total gain decreases with power. As observed in the transition from the 500 mW to the 1 W case, high powers make it more important to optimise parameter k_1. This effect is even more obvious at higher pump powers, while k_2 remains constant for the whole range of powers covered in Fig. 9.

Fig. 8 Optical gain contour obtained for the configuration determined with the simultaneous optimization of external pump powers and central pump position, for the case of 1 W total input power

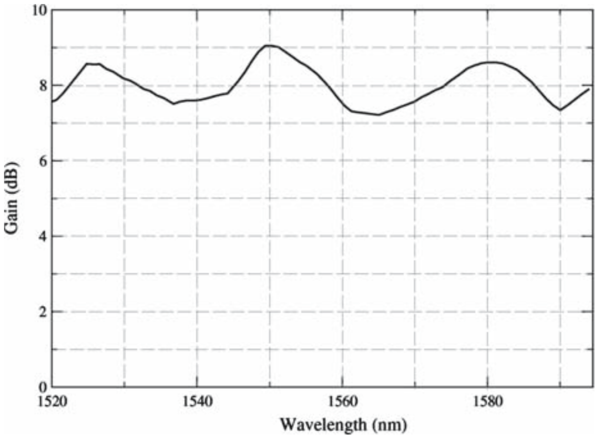
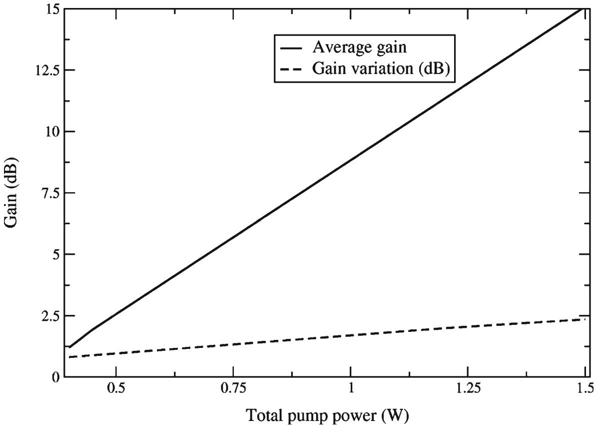


Fig. 9 Gain flatness and average gain over 75 nm versus total pump power, for the combined method



4 Conclusion

In conclusion, we have proposed and demonstrated a simple and efficient direct method to optimise the design of 3-wavelength Raman amplifiers. For a backward-pumped amplifier, we have determined the optimal power ratio for a pump with regularly spaced spectral components, and the optimal spectral locations for the individual pump components in the case where each delivers an equal power. The composite Raman gain spectrum resulting from the optimised 3λ-PS shows a gain variation below 1.8 dB over 75 channels in the 1,520–1,595 nm range, with an average on-off gain of 13.5 dB (obtained with a total pump power of 1 W). The proposed optimisation procedure is generic and can be applied in a range of similar problems.

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