Calculation of the effect of pump depletion in WDM systems with distributed Raman gain

A. V. Wesson and R. I. Killey

Department of Electronic and Electrical Engineering, University College London

Abstract: Raman amplifiers, which rely on the non-linear effect of stimulated Raman scattering, considerably improve transmission quality in comparison to current wavelength-division multiplexing (WDM) systems based on erbium-doped fibre amplifiers (EDFAs) and hence have potential use in future broadband networks. This paper investigates the effect of pump depletion when Raman amplification is used in a WDM system.

1 Introduction

As the demand for the capacity of optical fibre communications systems increases, both in terms of data rates and for geographic coverage, so does the demand for network bandwidth. Direct optical amplification of light signals carried in a fibre is of considerable interest for optical communications systems. The Raman amplifier is a specific type of fibre amplifier, which relies on the non-linear optical effect of stimulated Raman scattering. It has the advantages of self-phase matching between the pump and the signal and has both a broad-gain and a high-speed response compared with other non-linear processes [1]. These characteristics make the Raman amplifier attractive for use in high-bit rate WDM optical communication systems.

Different research groups have used different methods in the design of a backward-pumped Raman pre-amplifier for use in optical communications around 1.55µm. Hansen *et al.*[2] used a single Raman fibre pump laser with 1.0W power at 1453nm to provide gain over the range 1547.0-1562.5nm in a 123km dispersion-compensating fibre. The backward pumped amplifier within a receiver configuration is shown below. This arrangement gave a peak gain of 28.1dB and a ripple of 1.3dB peak-to-peak.

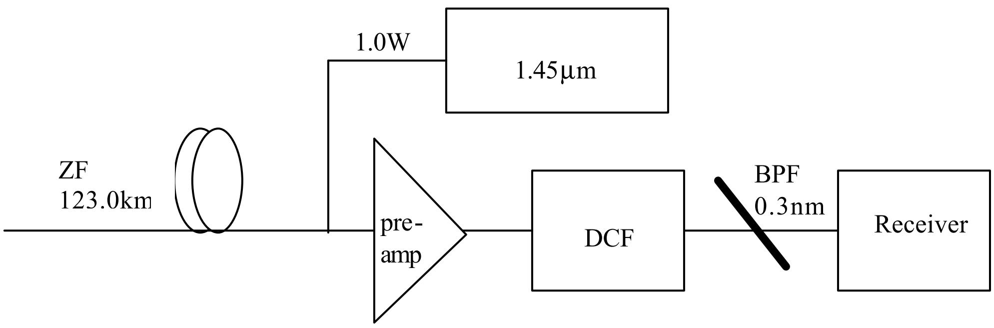


Figure 1: Single-pumped Raman amplifier [2]

The use of multiple Raman pump wavelengths allows a flat gain over a wide bandwidth, which is suitable for WDM signals. For example, Emori *et al.* [3] investigated the use of a counter-propagating 12-wavelength WDM pumping unit, which comprised of high-power GRINSCH strained-layer MQW buried-heterostructure laser diode modules with wavelengths from 1405 to 1510nm. Gain flattening was achieved by allocating more power to the shorter pump wavelengths. This system was tested using 25km of SMF/DSF or 20km RDF and gave a gain ripple of approximately ±0.5dB. The average gain was 2dB in SMF and 6.5dB DSF/RDF when a maximum total power of 2.2W was applied to the pump. In order to design a system with Raman amplification, it is important to be able to accurately predict the signal power profile throughout the system. This is done by computational simulation and the results are important for use in power budget calculations and in predicting the effect of non-linear distortion.

2. Theory

The interaction between the pump and Stokes waves in a Raman amplifier is governed by a set of two coupled equations [4]:

$$\frac{dI_S}{dz} = g_R I_P I_S - \alpha_s I_s \tag{1}$$

$$\frac{dI_P}{dz} = -\frac{\omega_P}{\omega_S} g_R I_P I_S - \alpha_P I_P \tag{2}$$

where I_P and I_S are the pump and signal intensities, g_R is the Raman gain coefficient and the absorption coefficients α_P and α_S account for fibre loss at the pump and signal frequencies respectively. Equation (1) can be solved to give an analytical equation for the signal power profile along the fibre. For a system with a counter-propagating pump, the pump intensity along a fibre of length L is given by equation (3) below.

$$I_P = I_0 \exp\left[-\alpha_P (L - z)\right] \tag{3}$$

I_0 is the pump intensity input into the fibre and z is defined as the forward direction of propagation of the signal. Substituting equation (3) into equation (1) and solving gives an equation for the signal power profile.

$$I_S(z) = I_S(0) \frac{\exp(g_R I_0 L_{eff})}{\exp(\frac{g_R I_0}{\alpha_P})} \exp\left[\frac{g_R I_0}{\alpha_P} \exp(-\alpha_P (L - z)) - \alpha_S z\right] \tag{4}$$

The effective interaction length L_{eff} is given by:

$$L_{eff} = \frac{1}{\alpha_P}\left[1 - \exp(-\alpha_P L)\right] \tag{5}$$

Equation (4) gives the power profile assuming negligible pump power depletion, i.e. no energy transfer to the signal. However a more accurate solution may be required, and hence a simulation program was written to predict the effect of this depletion. The simulation program calculating both signal and pump power profiles along the fibre was based on the coupled equations (1) and (2). A Matlab program was written to perform calculations of the distance-dependent power of the signal along a 100km length of fibre, with a backward Raman pump at the end of the fibre. The fibre loss at the signal wavelength was taken to be 0.2dB/km and the pump loss due to scattering to be 0.3dB/km. Starting with an exponential equation for the signal, the pump power was calculated at 1km steps along the length of the fibre and then these pump powers were used to calculate the new signal power at each of these steps. As the signal and pump powers are interdependent, an iterative numerical method was used to converge to the correct signal power profile. Fig. 2 shows the result of the simulation program assuming no depletion, compared to the analytical solution given by equation (4), validating the accuracy of the simulation.

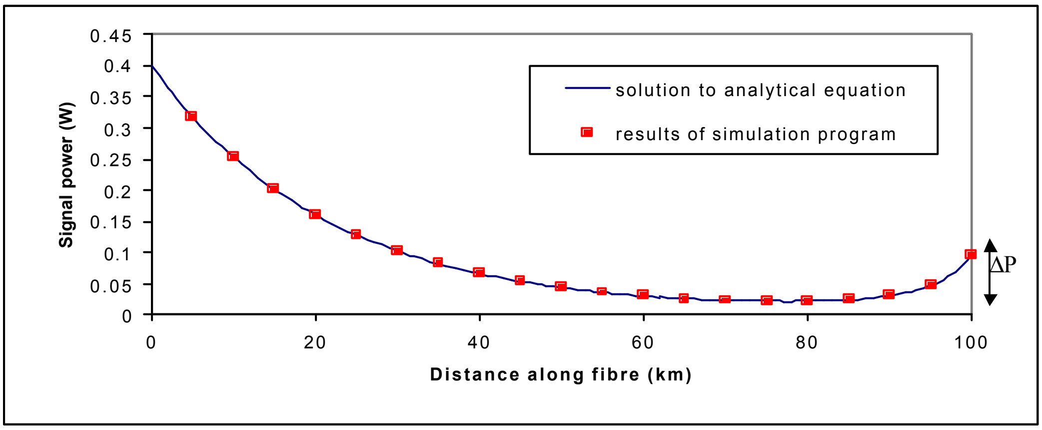
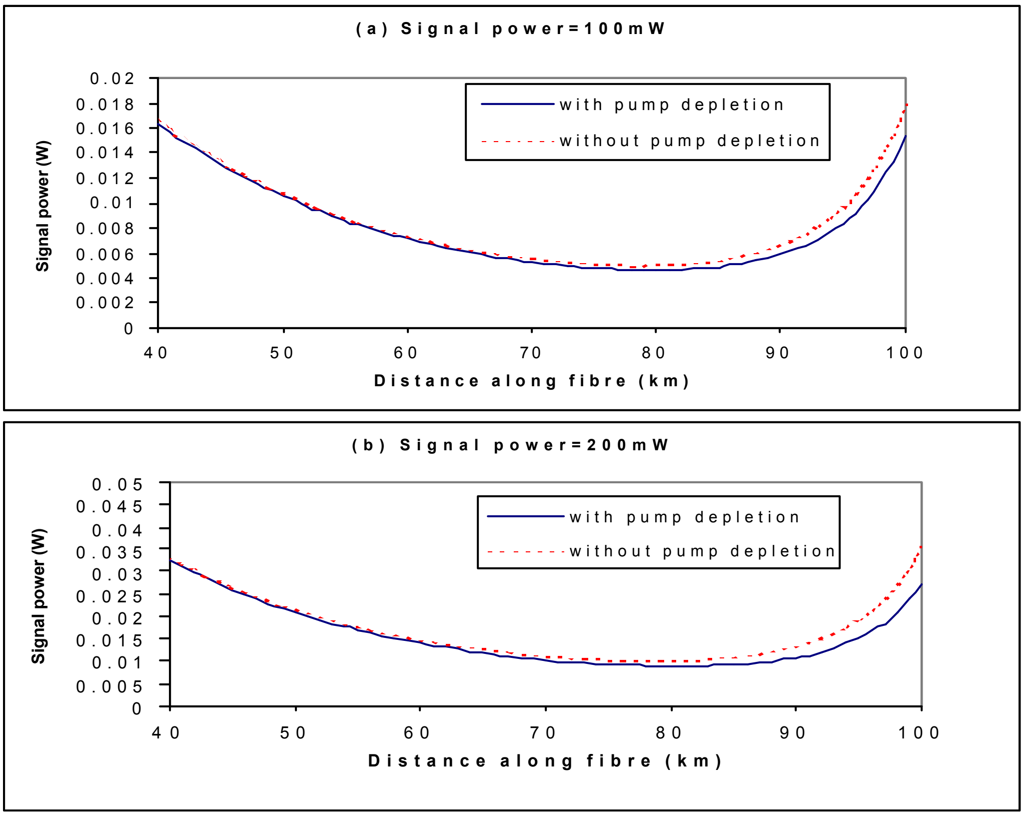


Figure 2: Comparison of results of simulation program to solution of analytical equation (equation (2)) for an input signal power of 400mW and an input pump power of 500mW.DP denotes the increase in received power at the end of the fibre due to Raman gain

3. Results

Pump depletion, the effect of power transfer from the pump to the signal, is however experienced in real systems. The impact of Raman pump power depletion can be estimated by comparing the results of simulations both with and without pump depletion, as shown in Fig. 3. From Fig. 3 and the percentage reduction of the received signal power due to pump depletion, plotted in Fig. 4, it can be seen that pump depletion becomes more significant at higher input signal powers, i.e. powers approaching that of the pump. The reduction in received signal power was 35% for 400mW signal power.



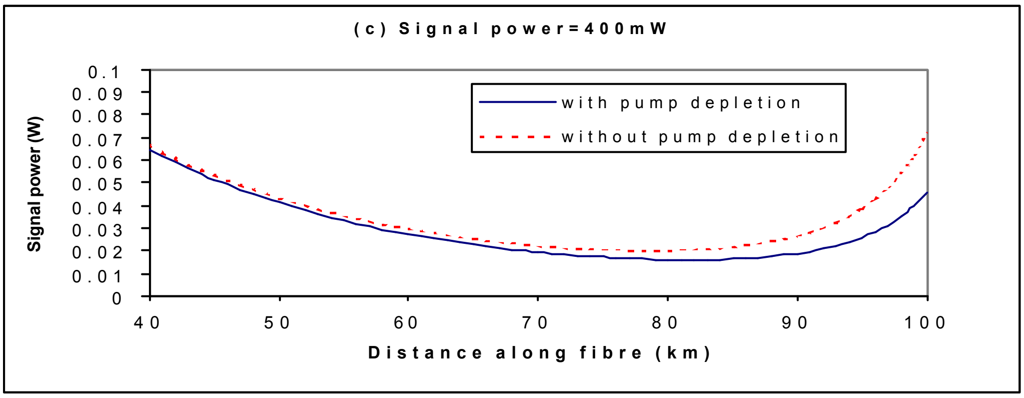


Figure 3: Comparison of signal distributions with and without pump depletion. In each case, the input pump power is 500mW. The input signal power is: (a) 100mW, (b) 200mW, (c) 400mW

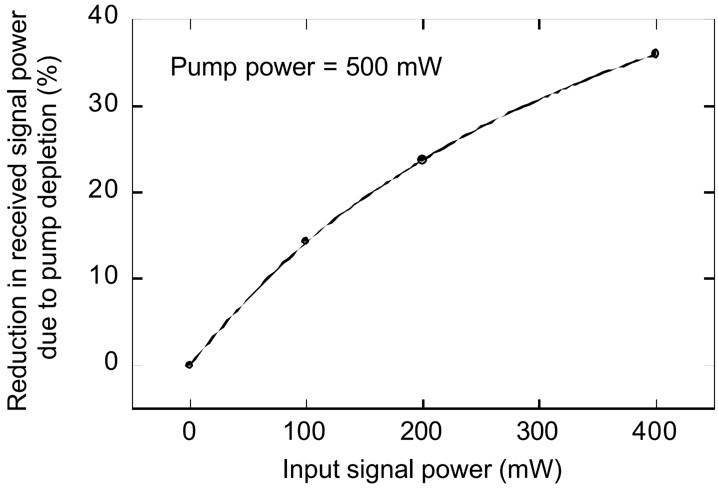


Figure 4: Percentage effect of pump power depletion on received signal power, for different input signal powers and for an input pump power of 500mW

4. Conclusions

This paper has shown that the effect of pump depletion within a Raman system can be simulated, using a model based on the coupled equations for the interaction between pump and signal power distributions. The pump depletion has a more significant effect at higher input signal powers, and must be taken into account in the design of systems with high signal powers. With 400 mW signal launch power, typical for WDM systems with >100 channels, transmitted over a 100 km span with a Raman pump power of 500 mW, the effect of pump power depletion accounted for a reduction in the received power of 35% compared to the value obtained analytically, ignoring the effect of depletion.

References

[1] Yasuhiro Aoki, 'Properties of Fiber Raman Amplifiers and Their Applicability to Digital Optical Communication Systems', Journal of Lightwave Technology, Vol. 6, no. 7, July 1988, pp.1225-1239

[2] P.B. Hansen, L. Eskildsen, S.G. Grubb, A.J. Stenz, T.A. Strasser, J.Judkins, J.J. DeMarco, R. Pedrazzani, D.J. DiGiovanni, 'Capacity Upgrades of Transmission Systems by Raman Amplification', *IEEE Photonics Technology Letters,* Vol.9, no.2, 1997

[3] Y. Emori, K. Tanaka, S. Namiki, '100nm bandwidth flat-gain Raman amplifiers pumped and gain-equalised by 12-wavelength-channel WDM laser diode unit', *Electronics Letters*, Vol.35, no.16, 1999

[4] Govind P. Agrawal, 'Nonlinear Fiber Optics', Second Edition, Academic Press, 1995