UNIFORM GAIN OF A MULTI-WAVELENGTH PUMPED WIDEBAND RAMAN AMPLIFIER IN OPTICAL COMMUNICATION SYSTEM

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ABSTRACT

Optical dense wavelength division multiplexing (DWDM) system employs distributed Raman amplifiers to amplify optical signals, which uses the stimulated Raman scattering effect in the fiber medium. This paper investigates Raman gain with forward pumping using only four pump lasers for an optical DWDM system. It is found that by selecting the pumps at 1390 nm, 1405 nm, 1418 nm and 1482 nm, a gain bandwidth of 65 nm from 1535 to 1600 nm can be achieved with a gain ripple of 0.9 dB, which covers the C-band and L-band.

1. INTRODUCTION

The rapid traffic growth traffic in optical fiber communication network has encouraged the development of dense wavelength division multiplexing (DWDM) to accommodate as many channels as possible within a single fiber [1-2]. Distributed Raman amplifier using the transmission fiber as the gain medium is a promising technology available for the optical long-haul DWDM communication systems, where simultaneous amplification of all the lightwave signals is required to compensate for the fiber loss [3-4]. As Raman amplifiers are distributed in nature rather then lumped like erbium doped fiber amplifiers (EDFA), the signal power can be maintained at an approximately constant level along the fiber [5]. Raman amplifier provides several advantages, such as low noise, simplicity, flexible use of signal wavelengths and broad gain bandwidth compared to EDFA [6]. Pumps used for Raman amplification may be constructed from semiconductor laser diodes or all fiber lasers [7]. Raman amplifier uses the stimulated Raman scattering (SRS) phenomenon, where a strong pump laser at shorter wavelength provides gain to signals at longer wavelengths [8]. Raman gain coefficient is strongly dependent on the frequency shift between the pump and signal frequencies. To obtain a flattened gain and broader spectrum, where all signals within the spectrum are equally amplified, multi-wavelength pump scheme is introduced [9]. By choosing appropriate pumping scheme, a usable bandwidth can be achieved for the wavelength range of 1500 to 1600 nm, where the transmission loss in the fiber is the minimum (0.2 dB/km).

The objective of this paper is to design a Raman amplifier for optical DWDM systems by selecting proper pump wavelength and pump power. The amplifier is analyzed with forward pumping employing four pump lasers to achieve a gain from 1535 nm wavelength to 1600 nm wavelength with minimum possible gain ripple.

2. SYSTEM ANALYSIS

The Raman amplifier configuration with forward pumping is shown in Fig. 1. The pump signals are launched into fiber through an optical coupler and propagate along with the information signals that are fed at the fiber input. The Raman amplifier utilizes the SRS effect in optical fiber to amplify the signals, which has the advantages of self-phase matching between the pump and the signal [1]. Raman scattering converts a small fraction of the incident power from an optical beam to another optical beam at a frequency downshifted by an amount determined by the vibrational modes of the medium. Incident light acting as pump for generating the frequency-shifted radiation is called stokes wave. For intense pump waves most of the pump energy will be converted to the stoke waves rapidly inside the medium [7]. A typical Raman gain spectrum for pure silica fiber is shown in the Fig. 2 for a pump wavelength of 1450 nm. It can be observed that the optical signal gain strongly depends on the Raman gain coefficient, which is a function of the wavelength.

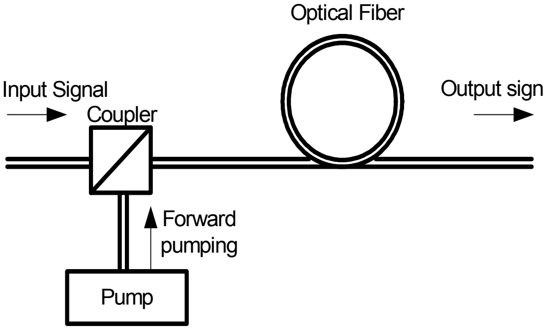

Fig. 1: Configuration of Raman amplifier system with forward pumping.

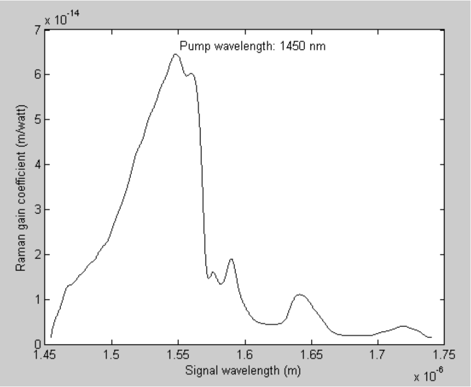

Fig. 2: Raman gain spectrum in a silica fiber with a single pump diode at 1450 nm [10].

The interaction between the pump and signal propagating in fiber is governed by the following two coupled equations [6]:

$$\frac{dS(f_s,z)}{dz}=\frac{g_r(f_s,f_p)S(f_s,z)P(f_p,z)}{KA_{eff}}-\alpha_s S(f_s,z) \quad (1)$$

$$\frac{dP(f_p,z)}{dz}=-\frac{f_p}{f_s}\frac{g_r(f_s,f_p)S(f_s,z)P(f_p,z)}{KA_{eff}}-\alpha_p P(f_p,z) \quad (2)$$

where $S(f_s,z)$ is the signal power at frequency f_s, $P(f_p,z)$ is the pump power at frequency f_p, α_s and α_p are the attenuation constants for the signal and pump, respectively, $g_r(f_p,f_s)$ is the Raman gain coefficient which depends on the frequency shift between the pump and signal, $\Delta f = f_p - f_s$, A_{eff} is the effective cross sectional area of the fiber and K is the polarization constant, which is 1 if the signal and pump are polarized and 2 if not polarized. The first term in Equation (2) represents the pump depletion due to the SRS effect, which can be neglected. Solving Equations (1) and (2), the Raman gain of a signal can be determined as

$$Gr=\exp\left[\frac{g_r(f_s,f_p)P(f_p,z)L_{eff}}{KA_{eff}}\right] \quad (3)$$

$$Gr(in\ dB)=4.343\frac{g_r(f_s,f_p)P(f_p,z)L_{eff}}{KA_{eff}} \quad (4)$$

where $L_{eff}=\{1-\exp(-\alpha_p L)\}/L$ represents the effective fiber length taking into account the fiber loss at pump wavelength.

A number of factors should be considered while designing a Raman amplifier with multi-wavelength pumps for DWDM systems, which include pump-to-pump power transfer, signal-to-signal power transfer, pump depletion, Rayleigh back-scattering, amplified spontaneous emission (ASE) noise, loss due to noise emission, and FWM in signals and pumps. The propagation equation for the signal with forward pumping is stated below, which neglects signal-to-signal power transfer, pump depletion, loss due to noise emission and FWM in signals and pumps.

$$\begin{aligned}\frac{dS_{fn}(f_{sn},z)}{dz}&=-\alpha_s S_{fn}(f_{sn},z)+\gamma_r(f_{sn})S_{bn}(f_{sn},z)\\&+S_{fn}(f_{sn},z)\sum_{i-1}^{m}\frac{g_r(f_{sn},f_{pi})}{KA_{eff}}P_{fi}(f_{pi},z)\\&+2hf_{sn}(\Delta f_s)\sum_{i-1}^{m}\frac{g_r(f_{sn},f_{pi})}{A_{eff}}(1+(e^{h(f_{sn}-f_{pi})/kT}-1)^{-1})\\&P_{fi}(f_{pi},z)\end{aligned} \quad (5\ )$$

where $S_{fn}(f_{sn},z)$, $S_{bn}(f_{sn},z)$ are the forward and backward power, respectively, of the nth signal at frequency f_{sn}, $P_{fi}(f_{pi},z)$ is the forward power of the ith pump, γ_r is the Rayleigh back-scattering coefficient of the nth signal frequency at f_{sn}; h, k, Δf_s are the Planck's constant, Boltzman's constant and spectral noise interval for noise increase, respectively. The pump-to-pump interaction can be described by the following equation:

$$\frac{dP_{fk}(f_k,z)}{dz}=-\alpha_p P_{fk}(f_k,z)+P_{fk}(f_k,z)\sum_{i=1}^{m}\frac{g_r(f_k,f_i)}{KA_{eff}}P_{fi}(f_{pi},z) \quad (6)$$

This equation was solved numerically to obtain kth pump power at various sections of the fiber.

3. RESULT AND DISCUSSION

The Raman gain for optical signals is evaluated using Equation (4). Figure 3 shows the Raman gain for a single pump at 1450 nm wavelength with input power of 0.25 watt, fiber length of 25 km and the Raman gain coefficient of Fig. 2. The gain is observed to contain a large ripple, which indicates that different signals will get amplified by different amount.

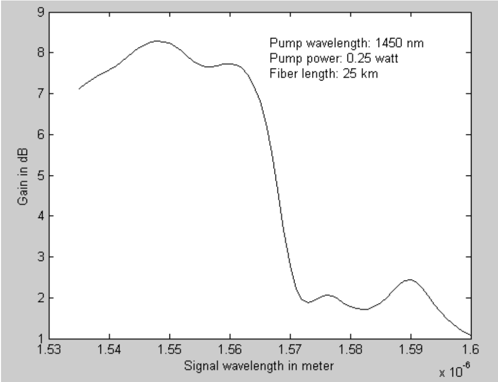

Fig. 3: Raman gain with a single pump diode at 1450 nm wavelength.

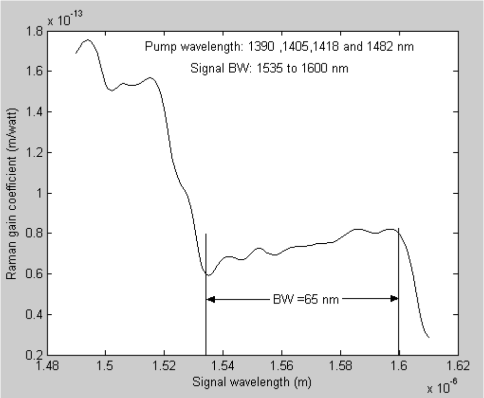

Fig. 4: Composite Raman gain spectrum with four pump diodes.

Therefore, to reduce the gain ripple, in other words, to make the gain uniform, multiple pumps are employed at different wavelengths. Here four pump lasers at wavelengths of 1390 nm, 1405 nm, 1418 nm and 1482 nm, respectively, are employed for this purpose. A composite Raman gain spectrum can then be evaluated by linear superposition of individual Raman gain spectrum at different wavelengths as shown in Fig. 4.

Next the pump powers are evaluated along the fiber using the Equation (6) considering fiber loss at pump wavelength to be 0.35 dB/km and pump-to-pump interactions due to Raman scattering. The transmission fiber of 25 km is divided into small sections so that the distance-dependent terms in Equation (5) can be assumed to be constant within any fiber section. Pump power is evaluated at the end of each section and this power is considered as the input power for the immediate next section. Using the evaluated pump power at each section and Raman gain co-efficient, the signal power is estimated using Equation (5) neglecting backward signal power.

The power variation of the four pump diodes are shown in Fig. 5. The input powers for the pumps are assumed to be 0.25 watt, 0.20 watt, 0.17 watt and 0.015 watt, respectively. It is observed from the figure that the pump-1 is attenuated the most as it has the highest frequency. Also the pump-4 has the lowest frequency and hence gets amplified at the expense of other pump powers. The corresponding Raman gain is evaluated as shown in Fig. 6. The gain is observed to be more uniform than that obtained in Fig. 3. However, a gain ripple of 1.334 dB is obtained with these conditions.

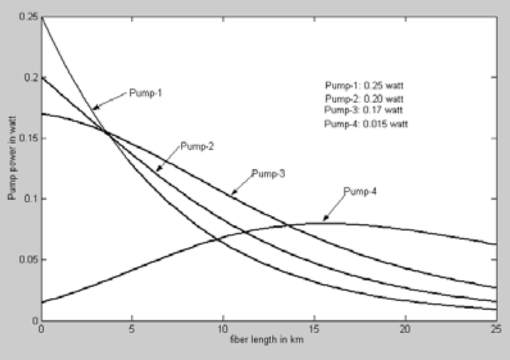

Fig. 5: Pump power variation with the fiber length.

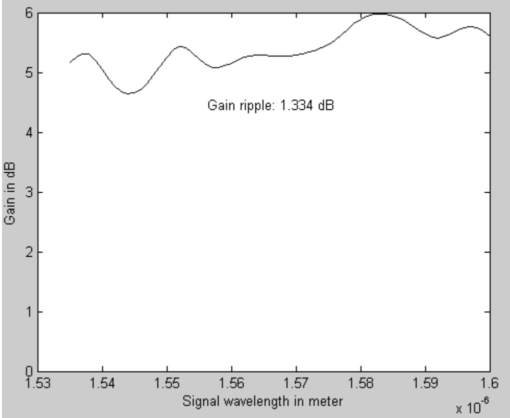

Fig. 6: Raman gain of the optical signals with four pump diodes.

Then the simulation is performed with different pump powers of 0.28 watt, 0.20 watt, 0.18 watt and 0.01 watt, respectively. The pump power variation along the fiber length is shown in Fig. 7. The corresponding Raman gain is evaluated and found to be improved as shown in Fig. 8. A gain ripple of 0.9 dB is observed with these system parameters.

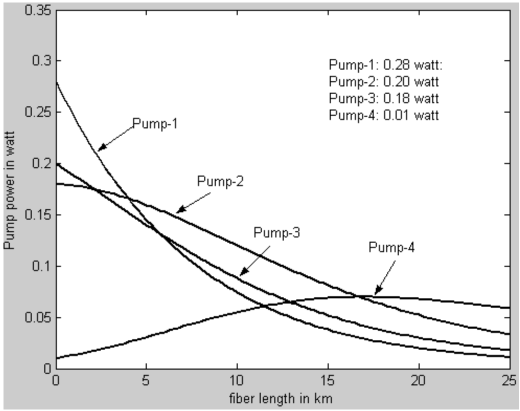

Fig. 7: Pump power variation with the fiber length.

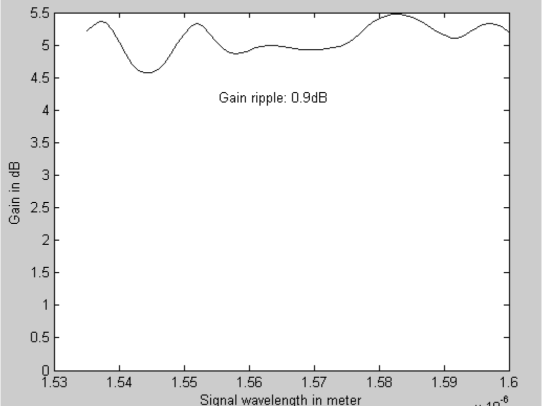

Fig. 8: Raman gain of the optical signals with four pump diodes.

4. CONCLUSION

The Raman gain of an optical signal is observed to depend on the selection of pump wavelength and pump power. First the pump wavelengths are selected to achieve the desired gain bandwidth with the help of the composite Raman gain spectrum. Then proper pump powers are chosen to reduce the gain ripple. It is observed that if the pump power is increased, the Raman gain is increased and the gain ripple is reduced. Again by selecting a different set of pump wavelengths, a different window of signal transmission wavelength can be achieved. The results of this paper can be extended by incorporating backward and bi-directional pumping in addition to the forward pumping utilized in this paper.

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