

## DESIGN OF RAMAN AMPLIFICATION WITH MULTIPLE PUMPING FOR OPTICAL DWDM SYSTEM

Mohammed Nazrul Islam and Mohammed S. Alam\*

Department of Electrical and Electronic Engineering, Bangladesh University of Engineering  
Dhaka 1000, Bangladesh, E-mail: nazrul@eee.buet.ac.bd

\*Department of Electrical and Computer Engineering, University of South Alabama,  
Mobile, AL-36688, USA, E-mail: malam@usouthal.edu

### ABSTRACT

Raman amplifier has been found to be an attractive candidate for optical dense wavelength division multiplexed system related applications. In the design of Raman amplifier, determination of wavelength and power of the required pumps are the major concerns. This paper investigates the effect of selection of the pump wavelength, power and pumping scheme on the gain spectrum and signal power conditions along the fiber. Based upon the simulation results, the design criteria for a Raman amplifier are proposed.

### 1. INFORMATION

The rapid growth of internet and data traffic in optical communication systems led to the development of dense wavelength division multiplexing (DWDM) technology to accommodate as many information channels as possible within a single fiber. To meet the ever increasing demand for information capacity, broad-bandwidth optical amplifiers are essential. Optical systems have been utilizing almost the entire gain bandwidth of existing erbium-doped fiber amplifiers (EDFA) and are now approaching the upper limit of transmission capacity [1]. Alternatively, Raman amplification in optical fiber has become as a promising technology with broader gain bandwidth and simple configuration [2]. Because of its distributed amplification, as compared to lumped amplification in EDFA, Raman amplifier provides a better system performance especially with respect to noise [3]. Distributed Raman amplifier can mitigate the fiber nonlinear effects and improve the signal-to-noise ratio without requiring any increase of the optical signal power [4]. Despite the simplicity of Raman amplifier architecture, many factors must be considered in the design of the amplifier [5]. The most important task

of the design process is to obtain the pump wavelength and pump power for achieving the various required characteristics [6]. So far research works reported in the literature dealt with the solution of the Raman propagation equation [4-5] and other effects, such as pump-pump four wave mixing [7]. However, to the best of our knowledge, no work has been reported showing the design aspects of pump wavelength and power.

The objective of this paper is to develop a design procedure for selecting the wavelengths and associated power of multiple pumps used in Raman amplifier. The effect of pump wavelength on the gain spectrum, and the impact of pump power on the signal power variation has been investigated to obtain the pump laser selection criteria for applications in optical DWDM communication systems.

### 2. ANALYSIS

Figure 1 shows the basic configuration of a Raman amplifier. It employs optical fiber as the gain medium. Pump lights are fed to the fiber through a coupler which propagate in the forward or in the opposite direction to the information signals.

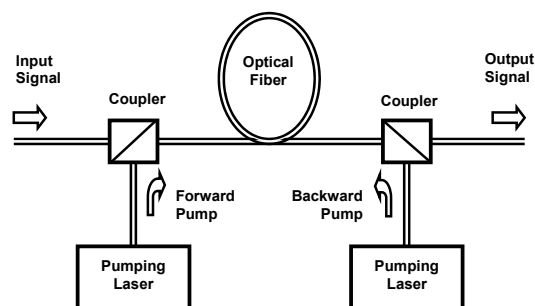


Fig. 1: Configuration of a Raman amplifier system.

Raman amplifier uses the stimulated Raman scattering effect in an optical fiber, where a strong pump laser at shorter wavelength provides gain to signals at longer wavelengths. As illustrated in Fig. 2, the Raman gain spectrum in fused silica fibers spread over 40 THz bandwidth with the peak gain at around 13.2 THz bandwidth. The gain spectrum shifts with the pump spectrum, while the peak gain coefficient varies inversely with the pump wavelength. Thus multiple pumps can be introduced at suitable wavelengths to achieve a flattened and broader spectrum.

A number of factors affect the design of a Raman amplifier, which include pump-to-pump power transfer, signal-to-signal power transfer, pump depletion, Rayleigh scattering and amplifier spontaneous emission (ASE) noise. The steady-state Raman amplified system incorporating the above effects can be described by a set of coupled nonlinear equations as shown below [3]:

$$\begin{aligned}
\frac{dP^\pm(z, \nu_i)}{dz} = & \mp \alpha(\nu_i)P^\pm(z, \nu_i) \pm \eta(\nu_i)P^\mp(z, \nu_i) \\
& \pm P^\pm(z, \nu_i) \sum_{m=1}^{i-1} \frac{g_R(\nu_m - \nu_i)}{\Gamma A_{eff}} [P^\pm(z, \nu_i) + P^\mp(z, \nu_i)] \\
& \pm \frac{g_R(\nu_m - \nu_i)}{\Gamma A_{eff}} [P^\pm(z, \nu_i) + P^\mp(z, \nu_i)] \\
& \pm h\nu \sum_{m=1}^{i-1} \times \left[ 1 + \left( e^{\frac{h(\nu_m - \nu_i)}{kT}} - 1 \right)^{-1} \right] \Delta\nu \\
& \mp P^\pm(z, \nu_i) \sum_{m=i+1}^n \frac{\nu_i g_R(\nu_i - \nu_m)}{\Gamma A_{eff}} \\
& \times [P^\pm(z, \nu_i) + P^\mp(z, \nu_i)] \\
& \pm \frac{\nu_i g_R(\nu_i - \nu_m)}{\Gamma A_{eff}} \\
& \mp 2h\nu_i P^\pm(z, \nu_i) \sum_{m=i+1}^n \frac{\nu_m}{\Gamma A_{eff}} \times \left[ 1 + \left( e^{\frac{h(\nu_m - \nu_i)}{kT}} - 1 \right)^{-1} \right] \Delta\mu
\end{aligned} \quad (1)$$

where  $P^\pm(z, \nu_i)$  and  $P^\mp(z, \nu_i)$  are optical power of forward- and backward propagating waves within infinitesimal bandwidth around  $\nu_i$ , respectively;  $\alpha$ ,  $\eta$ ,  $k$  and  $T$  are attenuation constant, Rayleigh backscattering coefficient, Planck's constant, Boltzmann constant and temperature, respectively;  $A_{eff}$  is the effective area of optical fiber at frequency  $\nu_m$ ;  $g_R(\nu_i - \nu_m)$  is Raman gain parameter at frequency  $\nu_i$  due to pump at frequency  $\nu_m$ ; the factor  $\Gamma$  accounts for polarization randomization effects, which lies between 1 and 2. Since spontaneous emission and thermal noise are not correlated with the signal, a factor of 2 is included in the noise terms (sixth term in the equation). The frequency ratio

$\nu_i/\nu_m$  represents vibrational losses. The terms from  $m=1$  to  $m=i-1$  and from  $m=i+1$  to  $m=n$  cause amplification and attenuation of the channel at frequency  $\nu_i$ , respectively. Here the frequencies  $\nu_i$  are numerated in descending order and  $\nu_1$  corresponds to the highest frequency or the shortest wavelength.  $\Delta\nu$  and  $\Delta\mu$  are spectral noise interval for the noise increase and loss, respectively. The first two terms in the right hand side of equation (1) denote the fiber loss and Rayleigh back-scattering, the third term represents the Raman gain due to shorter wavelength, the fourth term corresponds to the ASE noise with thermal factor, the fifth term represents the pump depletion due to longer wavelength, and the sixth term corresponds to the loss due to noise emission.

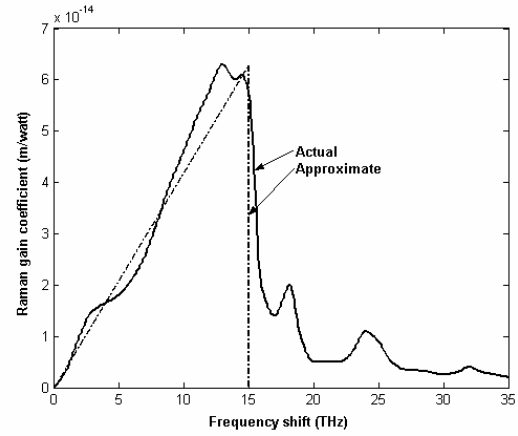
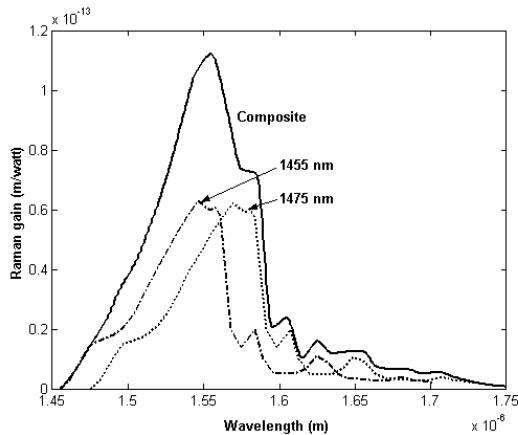


Fig. 2: Raman gain spectrum in fused silica fiber [1].

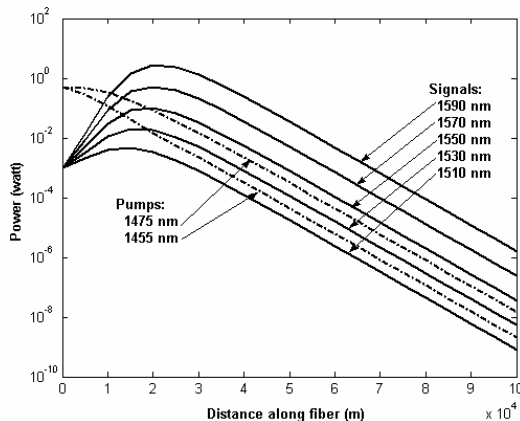
## RESULTS AND DISCUSSION

One of the major considerations for Raman amplifier design is the selection of pump wavelengths to realize the gain characteristics with minimum ripple and specific bandwidth. This can be achieved by a linear superposition of the gain curves of the individual pumps. In this paper, the Raman gain is simulated for different pump wavelengths and then the composite gain spectrum is evaluated utilizing two pump lasers at 1455 nm and 1475 nm wavelengths. It is evident from Fig. 3 that a reasonable gain is achievable for the signal wavelength range of about 1500 nm to 1600 nm. However, to make the gain spectrum ripple-free, more pumps need to be added at suitable wavelengths. In this way, addition of more pumps offers a greater degree of freedom and allows for less gain ripple, but at the cost of increased complexity and expense.

The other major consideration for the Raman amplifier design is the determination of pump power. It requires solution of the Raman propagation equation described earlier, which is computation-intensive. However, as the backscattering powers of pumps and signals are usually very low, spontaneous Raman scattering, Rayleigh backscattering and thermal factor can be reasonably skimmed in calculating the Raman gain profile [8]. With this consideration, equation (1) has been numerically solved using attenuation constant of 0.2 and 0.35 dB/km for signals and pumps, respectively, effective area of  $5 \times 10^{-11} \text{ m}^2$ , pump initial power of 500 mW, signal initial power of 1 mW and signal wavelengths of 1510 nm, 1530 nm, 1550 nm, 1570 nm and 1590 nm, and a transmission distance of 100 km. The Raman gain coefficient is approximated by a triangular function as shown Fig. 2 [6].



**Fig. 3:** Individual and composite Raman gain spectrum with pump lasers at 1455 nm and 1475 nm.

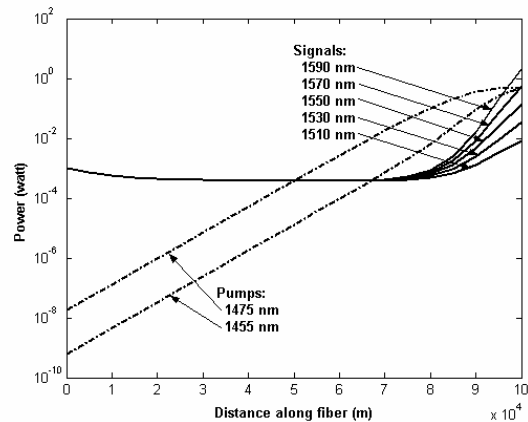


**Fig. 4:** Power variation of signals and pumps in case of forward pumping.

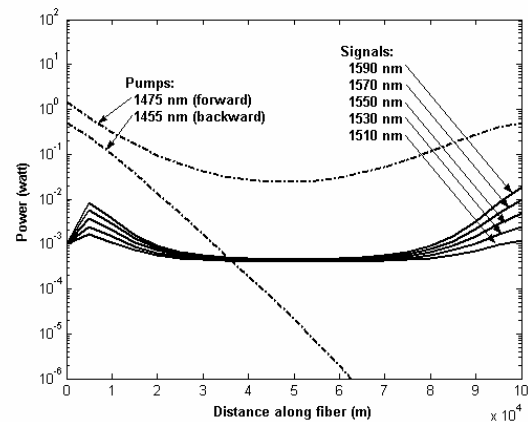
Figure 4 shows the pump and signal power variation in case of forward pumping. The pump powers are observed to decrease with distance due to

fiber attenuation. The optical signals get highly amplified at the beginning of transmission because of high pump power available. Gradually their power decreases because of fiber attenuation and less pump power available. It is also noted that different wavelength signals get amplified with different magnitude, which is due to nonuniform gain spectrum of the Raman amplifier.

Figure 5 shows the same characteristics for the case of backward pumping. Here the signals get less amplified at the beginning and highly amplified at the end of their propagation. Also, the difference in their amplification with respect to wavelength is insignificant except for last part of the transmission path.



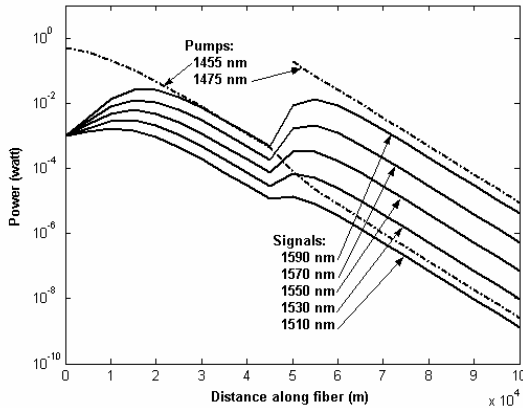
**Fig. 5:** Power variation of signals and pumps in case of forward pumping.



**Fig. 6:** Power variation of signals and pumps in case of bi-directional pumping.

Next, we studied the case of bidirectional pumping, where the 1455 nm pump is fed to the fiber from the front end and the 1475 nm pump is fed from the back end of the fiber. It is evident from Fig. 6 that the signal attenuation level for different wavelengths is more uniform than the previous two

cases. Finally, the case of distributed pumping is investigated, where the 1455 nm pump is fed to the fiber at the beginning and the 1475 nm pump is fed at a distance of 50 km from the transmitter. As shown in Fig. 7, the signals get power from one pump up to 50 km of transmission and then from two pumps for the rest of the transmission path. Therefore, distributed pumping offers better signal condition at the receiver end of the fiber as compared to forward pumping illustrated in Fig. 4.



**Fig. 7:** Power variation of signals and pumps in case of distributed pumping.

## CONCLUSION

The two major criteria for designing the pump for Raman amplification, namely, selection of wavelength and power, are investigated in this paper. It is observed that multiple pumps fed at suitable wavelengths can offer the desired broadband and uniform gain spectrum. However, the number of pumps should be decided based on the compromise between gain uniformity and cost. Backward pumping performs better than forward pumping with respect of signal power level and uniformity, whereas bidirectional pumping offers the best choice. In every case, distributed pumping from different points of the transmission path yields better

signal quality compared to single point pumping. Also, the pump powers may be set unequal to make the gain level more uniform. This work can be extended to do more powerful simulation involving an accurate model of the Raman gain, incorporating all other noise parameters and fiber nonlinear effects, to obtain the required pump wavelengths and powers more efficiently.

## ACKNOWLEDGEMENT

This research was supported by a grant from the National Science Foundation, USA (Award No: INT-0196468).

## REFERENCES

- [1] M. N. Islam, "Raman amplifiers for telecommunications," *IEEE J. Select. Topics Quantum Electron.*, vol. 8, no. 3, pp. 548-559, 2002.
- [2] H. Kidorf, K. Rottwitt, M. Nissov, M. Ma and E. Rabarjaona, "Pump interactions in a 100-nm bandwidth Raman amplifier," *IEEE Photon. Technol. Lett.*, vol. 11, no. 5, pp. 530-532, 1999.
- [3] S. Namiki and Y. Emori, "Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelength-division-multiplexed high-power laser diodes," *IEEE J. Select. Topics Quantum Electron.*, vol. 7, no. 1, pp. 3-16, 2001.
- [4] X. Liu and B. Lee, "A fast and stable method for Raman amplifier propagation equations," *Opt. Express*, vol. 11, no. 18, pp. 2163-2176, 2003.
- [5] P. Xiao, Q. Zeng, J. Huang and J. Liu, "A new optimal algorithm for multipump sources of distributed fiber Raman amplifier," *IEEE Photon. Technol. Lett.*, vol. 15, no. 2, pp. 206-208, 2003.
- [6] J. Bromage, "Raman amplification for fiber communications systems," *IEEE J. Lightwave Technol.*, vol. 22, no. 1, pp. 79-93, 2004.
- [7] J. C. Bouteiller, L. Leng and C. Headley, "Pump-pump four-wave mixing in distributed Raman amplified systems," *IEEE J. Lightwave Technol.*, vol. 22, no. 3, pp. 723-732, 2003.
- [8] X. Liu and M. Zhang, "An efficient method for two-point boundary value problems in Raman amplifier propagation equations," *Opt. Commun.*, vol. 235, pp. 75-82, 2004.