Shameem Saifuddin* and A Sivasubramanian

Performance Analysis of Distributed Raman Amplifier Using Different Pumping Methods in DWDM Communication Systems

Abstract: The objective of this work is to investigate and compare the impact of forward, backward and bidirectional pumping methods in repeater less distributed Raman fiber amplifier system and to analyze its benefits in long haul optical communication links. The effect of different pump wavelengths and pump powers are also analyzed. By adjusting the forward pump power as well as backward pump powers carefully, the transmission performance can be improved. The pump power ratio is adjusted to 20% so that the degradation of signal due to non-linear effect is reduced. The distributed gain and pump penetration depth for different pump power ratios are also examined. A comparison of different pumping methods reveals that bidirectional pumping gives the optimum performance in terms of higher gain and lower noise figure when compared to single pumps and unidirectional pumping. Low pump power ratios lead to better transmission performance than higher pump ratios due to lesser non-linear effects. The simulation results indicate that signal power evolution decreases with the increase in length of the fiber. It is also found that the pump power is more relevant during the first 50 km of the distributed fiber line and it decreases as it goes beyond 100 km. By choosing the optimum pumping methods and number of pumps, Raman Amplifiers can be used in almost all places where optical amplifiers are required.

Keywords: Raman fiber amplifier, gain, noise figure, gain bandwidth, bidirectional pump

*Corresponding author: Shameem Saifuddin, School of Electronics Engineering, Vellore Institute of Technology, Chennai, India,
E-mail: shameem.s2015@vit.ac.in
A Sivasubramanian, School of Electronics Engineering, Vellore Institute of Technology, Chennai, India,
E-mail: sivasubramanian.a@vit.ac.in

1 Introduction

The invention of Erbium doped fiber amplifiers revolutionized the optical communication systems a few decades ago. The origin of optical amplifiers dates back to the same as that of lasers, the only difference being the presence of a feedback in the latter. Research on Raman amplification for optical fiber communication systems started in early 197 as and its benefits were established by mid-1980s [1]. However, Raman amplifiers did not gain much commercial deployment primarily due to the requirement of high energy pump lasers as sources to achieve appreciable gain [2]. Contrary to the doped amplifiers like EDFA, Raman Fiber Amplifiers work on the principle of non-linear effect called Stimulated Raman Scattering (SRS) which does not require the presence of any special dopant in the fiber. When a signal enters a transmission fiber at very high energy level, it is affected by the non-linearities [3]. On the contrary, if the signal energy is less, it suffers from high noise. In lumped amplifiers such as EDFAs where the gain is lumped at a particular area of the medium, it is more complex to solve this problem than in distributed amplifiers such as Raman amplifiers [4]. Moreover, Raman fiber amplifiers are capable to retain the signal gain level over a very long transmission line [5].

The primary advantage of such a system is that the transmission fiber itself turns into an amplifier. Distributed Raman fiber amplifiers (DRA) are reported to have better signal quality when compared to conventional EDFAs and enables us to use higher order modulation formats [6, 7]. Such systems are highly flexible as it allows the researchers to fix the appropriate frequency or bandwidth by choosing the suitable pump power. Another advantage is the improved Optical Signal to Noise Ratio (OSNR). In DRAs, the amplification occurs through the transmission fiber itself and because of this, the signal power does not reach very low values consequently improving the OSNR. With these advances, the commercial use of Raman Amplifiers in the long haul and ultra-long haul fiber optic communication systems was made possible [8]. Though there are different types

of non-linearities which affect the optical communication system, the non-linear phenomenon which degrades the Raman amplifier performance is Rayleigh scattering. It is found in all fibers and since the amplifier mentioned in the document is a distributed amplifier, the same gets amplified over the length which results in enhanced noise and cross talk.

In order to amplify an input signal, a pump wavelength of appropriate power should be chosen. The pump and signal may be either co-propagating as in case of forward pumping or counter propagating as in case of backward pumping or both in case of bidirectional pumping. For larger optical power levels, the SRS non-linear effect will transfer a main portion of the applied pump power to the signal. If the backward and forward pump power is carefully adjusted, the performance in transmission is found to be improved. The pump power required to achieve a particular Raman gain is dependent on Raman gain coefficient, polarization, length of the fiber, fiber losses due to pump depletion and wavelength [8]. Less RIN (Relative intensity noise) is very important in fiber optic communication systems as it describes the power level of the amplifier [9]. In this paper, we investigate the performance of a Raman Amplifier using different multiple pumping schemes which include bidirectional as well as unidirectional pumping.

There are various applications of an optical amplifier including booster amplifier, pre amplifier and in-line amplifier [8]. Each of the above application requires a different set of gain and noise figure parameters. A booster amplifier is used along with a WDM (Wavelength Division Multiplex) link where the signal gets attenuated by the multiplexer [10]. The gain can be as low as 5–15 dB with output power as high as 20 dBm for a 40 channel system. For working as a pre amplifier, which is used at the end side of the communication link, optical amplifier should have high gain ranging around 30 dB and should have low noise figure between 4 and 5.5 dB so that the signal can be detected without much error. For transmission links above 150 km, in-line amplifiers are placed every 80–100 km range to ensure error free transmission in the optical fiber communication systems. For optical amplifiers to work as in-line amplifiers, they require moderate gain in 15–25 dB range and noise figure in the range of 5–7 dB [8].

The rest of the paper is organized as follows. The explanation of bidirectional pumping is given in following Section 2. Then the experimental set up is detailed and analyzed with different pump power ratio and pump wavelengths in Section 3. Four different setups are analyzed and compared in terms of SNR and gain of the amplifier [8] and Section 4 concludes the paper.

2 Bidirectional pumping in distributed Raman fiber amplifiers

Raman Effect describes the inelastic scattering of the optical photons. The basic equation governing Raman amplification is described in [1] and [2] .

$$\frac{dI_s}{dz} = G_r I_p I_s - \alpha_s I_s \tag{1}$$

$$\frac{dI_p}{dz} = -\frac{f_p}{f_s} G_r I_p I_s - \alpha_p I_p \tag{2}$$

where G_r is the Raman gain coefficient, I_p and I_s are the pump and signal intensities. f_p and f_s are the frequencies of pump and signal and α_p and α_s are the pump and signal attenuation constants, respectively. Raman Effect is the result of third order non-linearity [1]. The working principle of Raman fiber amplifier is based on Stimulated Raman Scattering, which is a non-linear effect and it requires an optical power higher than a threshold of at least 500 mW. Raman scattering occurs when a pump photon with frequency ω_p scatters a photon and leads to transfer of energy and momentum by which the incoming photon frequency gets converted to a new frequency ω_s, where $\omega_s = \omega_p + \Omega$, where $\Omega \ll \omega_p$. If $\Omega < 0$, it is called Stokes wave and anti-Stokes if $\Omega > 0$. Raman gain is the result of the Stokes shift corresponding to the difference in the pump and signal wave which needs to be amplified. The system designer can select the desired frequency or bandwidth by selecting the appropriate pump power. For a bidirectional pumping amplifier, the pump power is calculated as [7]

$$P_p(z) = P_0 \left(re^{-\alpha_p z} + (1-r)e^{-\alpha_p(L-z)} \right) \tag{3}$$

where r denotes the pump power ratio, z denotes the distance variable and L represents the length of the fiber. The pump power ratio is defined as the ratio of pump power (for a particular pump wavelength) to the total pump power used in the system. The pump power for different pump power ratios is plotted as a function of distance in Figure 1(a). The analysis shows that in all the cases, the gain is significant for lower pump power ratios. As the length of the fiber is increased, the pump power is attenuated at a rate of 0.25 dB/km. The gain profile is the integration of eq. (1), which is shown in the Figure 1(b) [1].

It may be observed that gain increases with increasing pump power ratio. All types of amplifiers generate noise during the process of amplifying the signals which results in more noise in the output signal than the input signal.
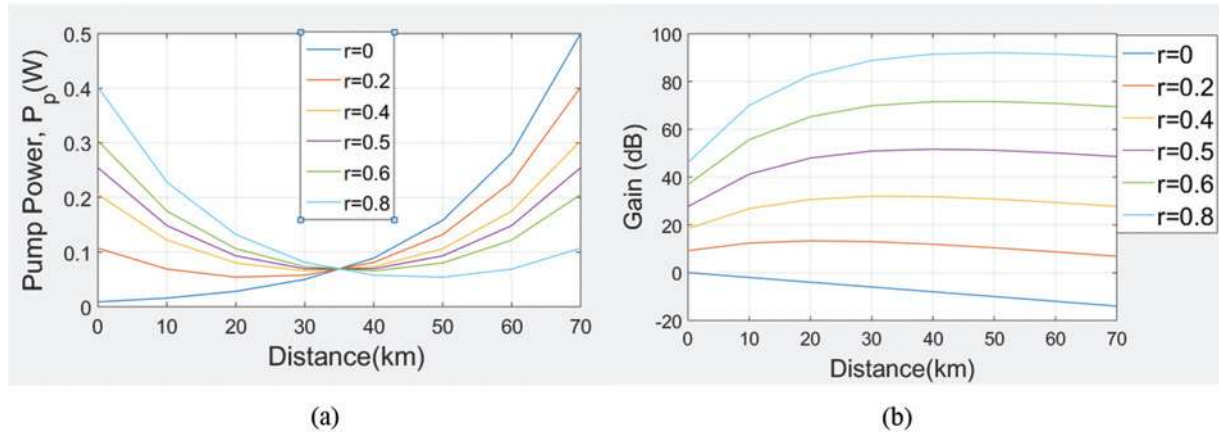
Figure 1: (a) Pump power distribution for bidirectional pumping in Raman Amplifier for different pump power ratio. (b) Gain Distribution for a Raman Amplifier with 70 km propagation distance for different pump power ratio.

Noise figure of an amplifier is the measure of how much the signal is degraded after amplification. When the pump and signal wave are travelling in the same direction, it is defined as forward pumping and if both are travelling in opposite direction, it is defined as backward pumping. For Raman Gain, the power conversion efficiency as well as the overall gain of the amplifier is dependent mainly on the average excitation density throughout the fiber length [11]. For bidirectional pumping, both the backward and forward pumping are used simultaneously.

When a signal of particular wavelength is allowed to propagate through a transmission fiber with no loss, the optical signal to noise ratio (OSNR) at the input side and at the receiver end will be same and so the Noise figure, which is the ratio of input OSNR to output OSNR will be equal to unity. But in practical cases, the transmitted signal is affected by losses in the fiber and therefore a high gain is required to amplify the signal. But to attain a high gain at the receiver end of the amplifier, high pump power is needed which results in more ASE (Amplified Spontaneous Emission) and other generated noises. In 2001, Y Emori et al. experimentally demonstrated the bidirectional scheme that realized both flat gain and low noise figure [12].

media. Different methods of multiple pumping are analyzed. All setups were analyzed with two sets of wavelength in the range of 1420 nm–1495 nm pump wavelength [1]. The first set up consisted of five CW laser pumps with optimal wavelengths 1420 nm, 1435 nm, 1450 nm, 1465 nm and 1495 nm as pump wavelengths for all the simulations and the signal wavelength is taken around 1550 nm. The second setup consist of pump wavelength 1445 nm,1450 nm,1465 nm,1480 nm and 1490 nm. An ideal optical MUX is used to feed the pump wave to the amplifier. The bandwidth taken is 70 nm and a 70 km distributed Raman Fiber Amplifier with zero dispersion is used in the setup.

The modulator used is Mach-Zehnder modulator with zero phase shift and zero insertion loss. The advantage of bidirectional pumping in DWDM systems is studied. Simulation set up with different number of pumps, unidirectional and bidirectional pumping with different pump power ratio are also examined. The pump power ratio is adjusted to 20% so that the degradation of signal due to nonlinear effect is reduced [12]. It is found that the forward pumped Raman amplifier has better noise figure and backward pumping gives better gain [13].

3 Performance evaluation of DWDM multipumped Raman amplifier

The simulation setup done in RSoft OptSim™ (Synopsys Inc.) software consists of 40 Gbps,40 channel DWDM link with an inter channel spacing of 50 GHz at a bit rate of 1 Gbps. NRZ modulation is chosen as it is found to be more advanced than RZ technique in optical transmission

3.1 Setup 1: bidirectional multiple pumping with equal number of pumps

Bidirectional multiple pumping is analyzed with equal number of forward and backward pumps with optimal pump power so that the pump power ratio is fixed at 20%. The setup is shown in Figure 2 and analyzed with different pump power ratios and pump wavelengths. From Figure 3 (a) and 3(b), it is found that the signal distortion is less
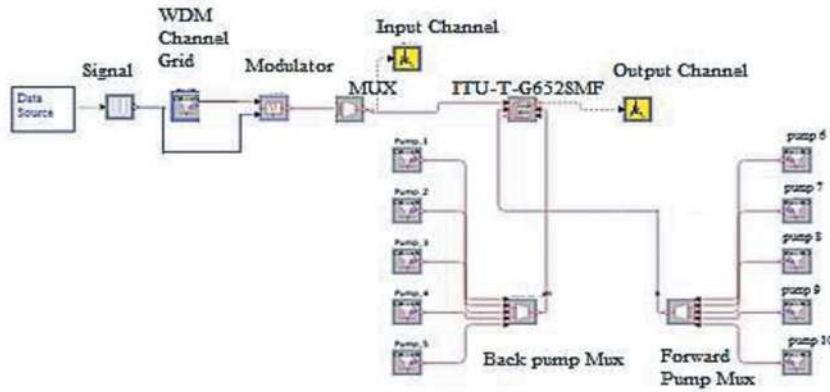
Figure 2: Bidirectional pumping with equal number of forward and backward pumps.
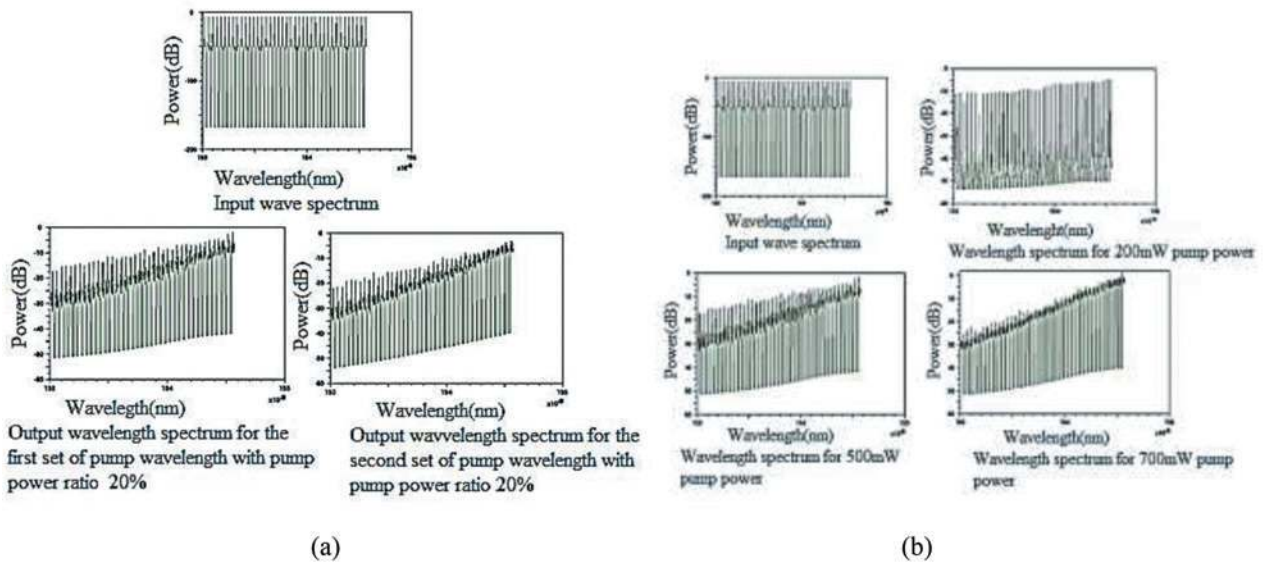

(a)

(b)

Figure 3: (a) Wavelength Spectrum for bidirectional pumping with equal number of forward and backward pumping using different set of pump wave lengths. (b) Wavelength Spectrum for bidirectional pumping with equal number of forward and backward pumping using different pump power values.

when the pump power is set at a low optimum value [12]. The first set of wavelength has more equalized gain output than the second set of wavelengths for same pump power ratio as seen in Figure 3(a). The backward absolute gain was found to be −1000 dBm/GHz and forward absolute gain was found for the wavelength range of 1535–1555 nm around 2.77 dB. Forward gain for the wavelength 1553–1554 nm is found to be 23.61 dB which is a moderate gain for working as an in- line amplifier. But from the setup, the forward effective noise figure for the wavelength range of 1538–1553 nm is 10.93 dB, which is very high in case of fiber amplifiers and forward SNR for the range of wavelength is 43. 01 dB. Table 1 shows the gain and noise figure parameters using different pump powers for the second set of wavelengths for

bidirectional pumping with equal number of forward and backward pumps. The output signal distortion increases

Table 1: Parameters of bidirectional pumping with equal number of forward and backward pumping using different set of pump wave lengths set 2.

Pump power	200 mW	500 mW	600 mW	800 mW
Forward absolute gain (dB)	−7.1	2.42	3.51	4.65
Forward gain(dB)	13.88	22.17	24.04	24.22
Forward effective NF	−10.09	−8.22	−10.7	−11.39
Forward On-Off gain	30.78	40.04	41.43	40.04
Forward SNR	40.22	42.11	41.90	42.20

with increase in pump power even when the pump power ratio was fixed at 20%. Though the gain is high, the noise figure (NF) is very high for higher values of pump.

The main advantage of using multiple pumping methods for Raman Amplifiers is a flat gain and it is achieved when the pump power is kept at a low value than high pump power values [12]. The noise figure and gain for different pump power is analyzed and is found that the signal is distorted most when the pump power ratio crosses 50%.

The noise figure for set 1 wavelength is found to be maximum for 1435 nm, whereas it is linear in the case of second set of wavelength. The plots for gain and noise figure are linear for the wavelength set 2 as seen in the Figure 4(a) and 4(b).

The gain of a Raman Amplifier is related to the effective fiber length, pump power and fiber area. On-Off gain, in most cases can be defined as the ratio of the output signal powers when the laser is turned 'on' and 'off'. [14]. The Raman ASE noise has little effect on the measured signal value with the pump laser "on". Since the measured spectral width is large, the noise will be predominant, then on-off gain can be calculated using the eq. (4). The Raman on/off gain is often referred to as the Raman gain.

$$G_{Ron/off} = 10\log$$
$$\left(\frac{P_s(pump.on, signal.on) - P_{noise}(pump.on, signal.off)}{P_s(pump.off, signal.on)}\right) \quad (4)$$

We can calculate both forward and backward on-off gain from the above setup. The on off gain (Figure 5(a) is not uniform for the first set of wavelengths while it is more linear for the second set of wave length. Figure 5(b) shows the forward and backward SNR for both the set of wavelengths.

From the plot it is clear that the SNR is more or less same for both sets of wavelengths.

3.2 Setup 2: unidirectional pumping

In this setup, five pumps with wavelengths ranging from 1420–1495 nm with optimal power is used only in one direction. The block diagram representation for multiple backward and multiple forward pumping is given in Figure 6(a) and 6(b), respectively. Both the setups were analyzed using the two sets of wavelengths as mentioned above. Figure 7 shows the output wave spectrum for the two setups with same pump power ratio. It is evident from the spectrum that the backward pumping is better in performance than the forward pumping. The SNR, gain and NF are also analyzed for both setups.

The forward absolute gain for the backward pumping in the wavelength range 1535–1555 nm is found to be −6.25 dBm/GHz and forward gain is found 14.65 dB and forward on-off gain as 31.3 dB. The forward effective noise figure is found as −0.22 dB which is too less when compared to the normal 3 dB noise figure and forward SNR is found to be 36.68 dB. For forward pumping setup the forward absolute gain in the range of wavelength 1535–1555 nm is found to be −14.06 dBm/GHz and forward gain is found as 7.62 dB. Forward on-off gain is found as −23.13 dB. The forward effective noise figure is found as −11.23 dB and forward SNR 43.17 dB

The noise figure is very less for the backward pumping and gain is moderate when compared to the forward unidirectional pumping. Also from the output wave spectrum, we can see that the backward pump setup output
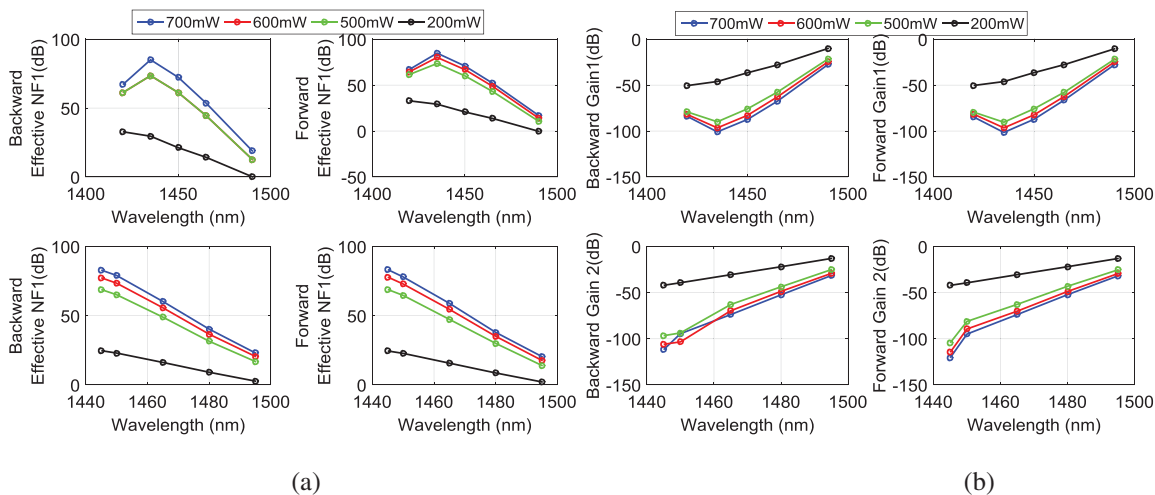

Figure 4: (a) Noise Figure for different pump power ratio in bidirectional pumping. (b) Gain for different pump power ratio in bidirectional pumping method.
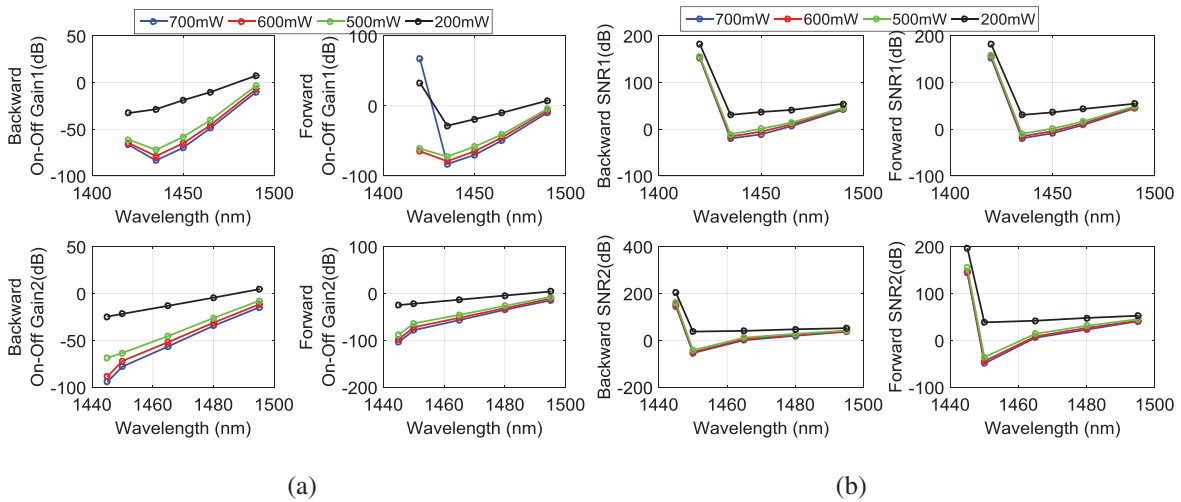
Figure 5: (a) On-Off gain for different pump power ratio in bidirectional pumping method. (b) SNR for different pump power ratio in bidirectional pumping method.
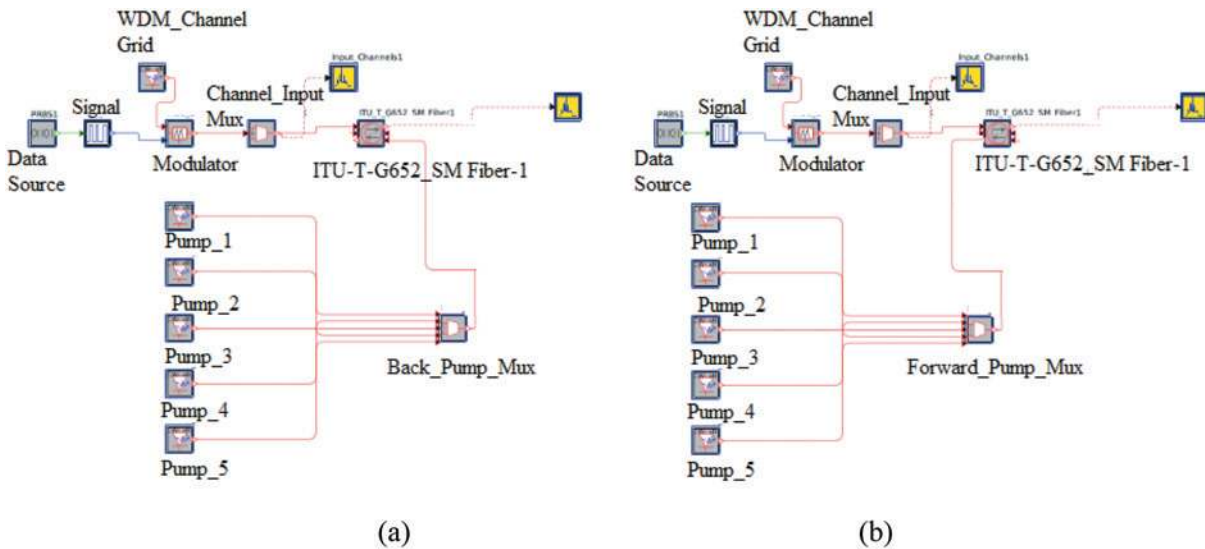

Figure 6: (a) Block diagram of multiple pumping in backward direction only (b) Block diagram for multiple pumping in forward direction only.
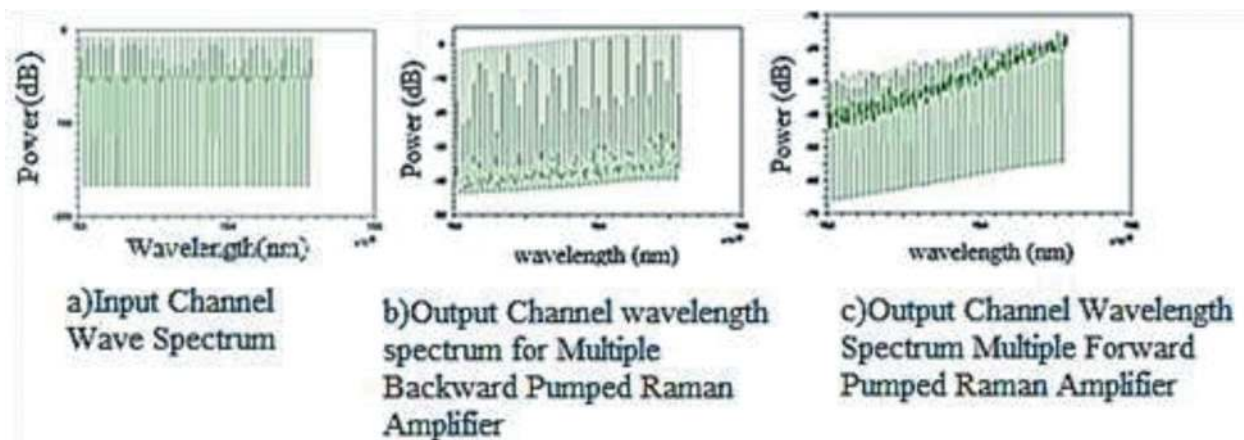

Figure 7: Input and output wave spectrum for multiple unidirectional pumping.

wave spectrum is less distorted than the one with forward pumping. All the pump wavelengths and power are same for both types of setups.

Next we analyze the second set of wavelengths. For no forward and multiple backward pumping at 20% pump power ratio, the forward gain in the signal rage of 1535–1555 nm wave length was found to be −19.55 dB. The forward effective noise figure was 0.24 dB and forward SNR of 36.09 dB. There is no significant variation from the values of two setups. Similarly, for the no backward multiple forward pumping setup the forward gain was around 11.13 dB in the 1535–1555 nm range. The forward effective noise figure is found to be as high as-09.04 dB and forward SNR as 44.19 dB.

Figure 8(a) and 8(b) contain the plots for noise figure and gain for the first set of wavelengths and Figure 9(a) and 9(b) shows the gain and noise figure plots for the different pump values used for the second set of wavelengths. The SNR for both set of wavelengths are comparable, while the noise figure is linear for the multiple backward pumping. Noise figure is the measure of excess noise which got added to the signal and it is the ratio of input SNR to output SNR in dB [15]. NF for both sets of wavelengths are very less in the forward multiple pumping systems, as the forward pumping is found to have better noise performance [16].

3.3 Setup 3: bidirectional pumping with unequal number of pumps

Here we analyze two setups with two sets of wavelengths as described above. Firstly, five numbers of pumps with optimal power is used in backward direction and single pump

with 1420 nm wavelength is used in the forward pumping (Figure 10). The second setup consists of five pumps in the forward direction and 1420 nm wavelength pump in the backward direction (Figure 11). These two setups are analyzed with two sets of wavelengths. Here also we found that as the pump power ratio is increased the signal distortion also increases. And if the pump power ratio is below 20%, then the distortion is increased. It is evident from the input and output wavelength spectrum that the bidirectional pumping with more number of backward pumps and single forward pump has produced less distorted output and found to be the best promising pumping method. Figure 12(a) plots the SNR and gain values for the setup with single backward pumping with multiple forward pumping and Figure 12(b)contains the SNR and Gain plot for multiple backward with single forward pumping method.

From the wave spectrum analysis (Figure 13) it is obvious that equalized gain is more prominent in bidirectional pumping with multiple pumps in the backward direction. For the first set of wavelengths, for bidirectional pumping with single forward pumping and multiple backward pumping it was found that the forward absolute gain in the range of wavelength 1535–1555 nm is −3.9 dBm/GHz and forward gain is found to be 18.31 dB. The forward on-off gain is found as 31.56 dB. The forward effective noise figure is found as −3.8 dB and forward SNR 40.51 dB. For the second reverse case where we used single backward pumping and multiple forward pumping it was found that the forward absolute gain in the range of wavelength 1535–1555 nm is found to be 8.35 dBm/GHz and forward gain is found 12.26 dB. Forward on-off gain is found to be 18.8 dB. The forward effective noise figure is found as −6.89 dB and forward SNR 41.17 dB
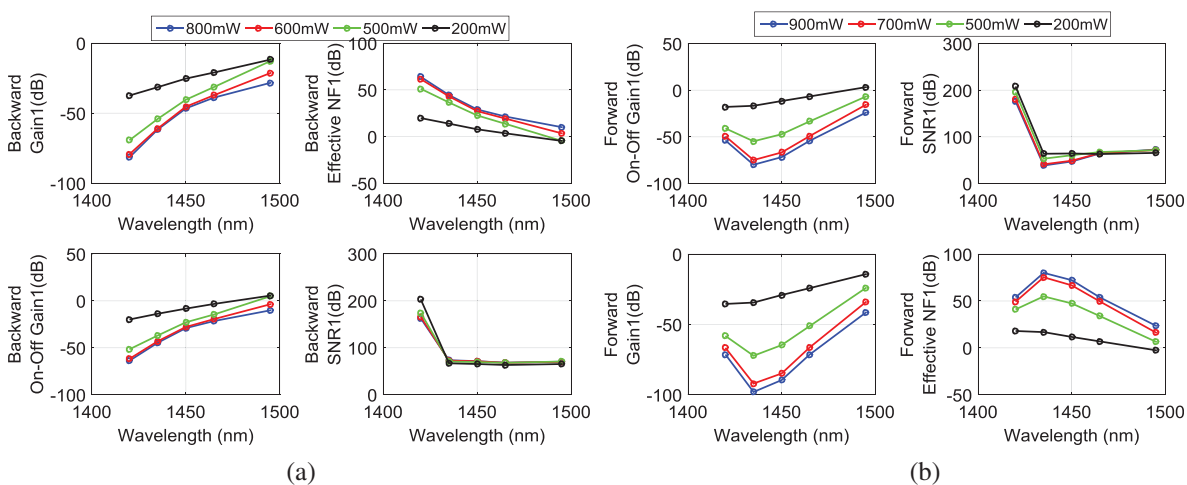

Figure 8: (a) Gain and NF plot for no forward pumping and multiple backward pumping (Wavelength Set 1) (b) Gain and NF plot for no backward pumping and multiple forward pumping (Wavelength Set 1).
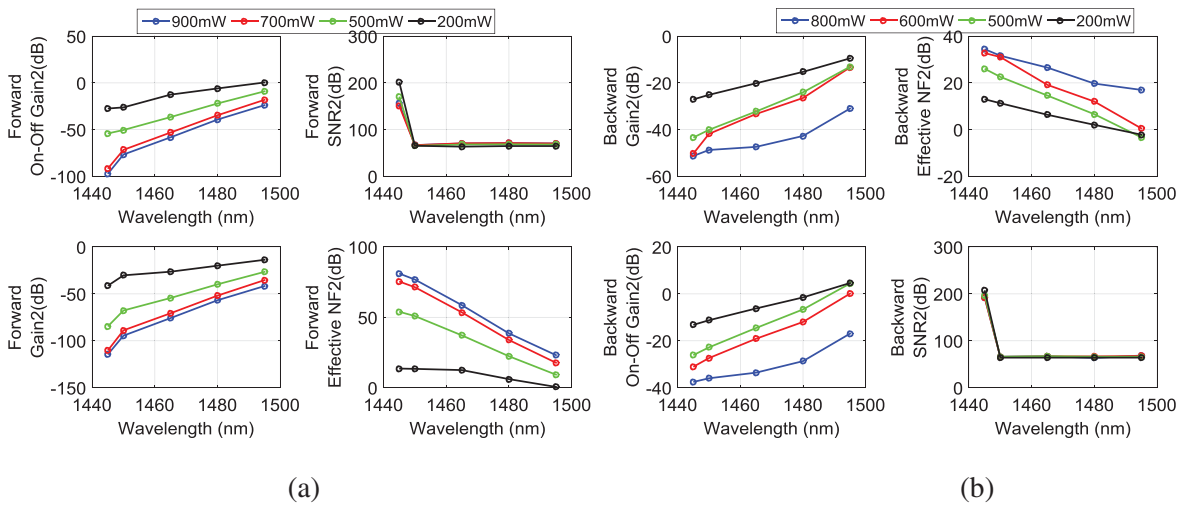
Figure 9: (a) Gain and NF plot for no backward pumping and multiple forward pumping (Wavelength Set 2) (b) Gain and NF plot no forward pumping and multiple backward pumping (Wavelength Set 2).
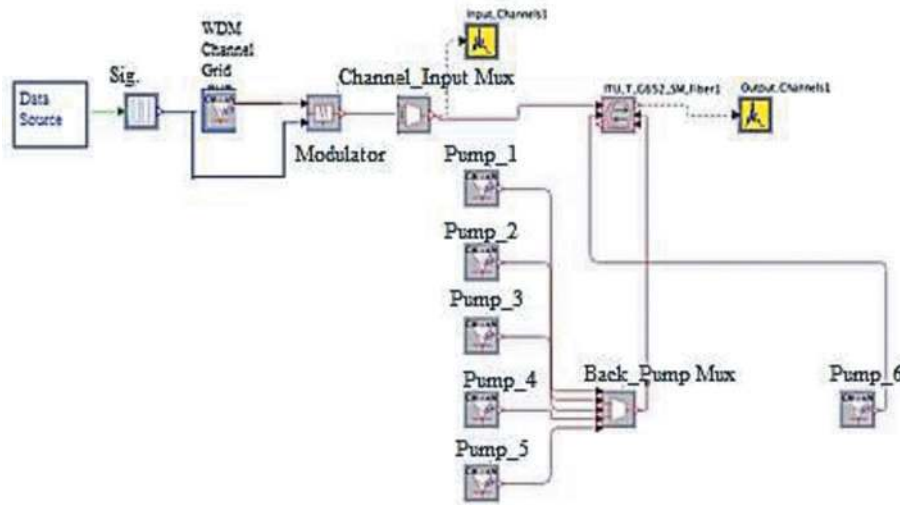

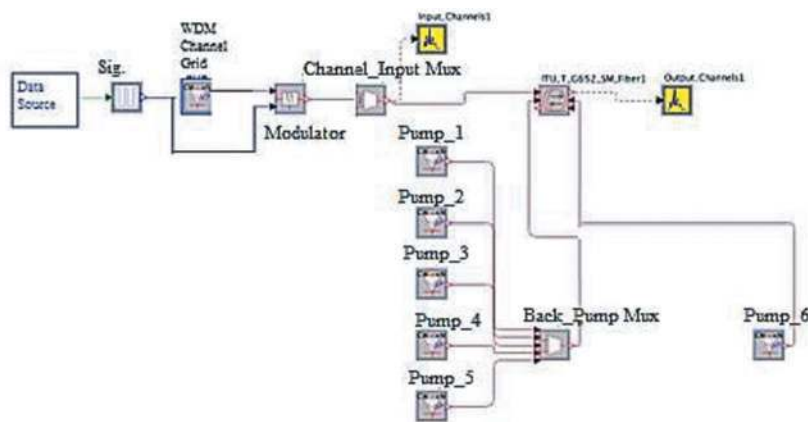**Figure 10:** Bidirectional pumping with single forward pump and multiple backward pumps.

Figure 11: Bidirectional pumping with single backward pump and multiple forward pumps.
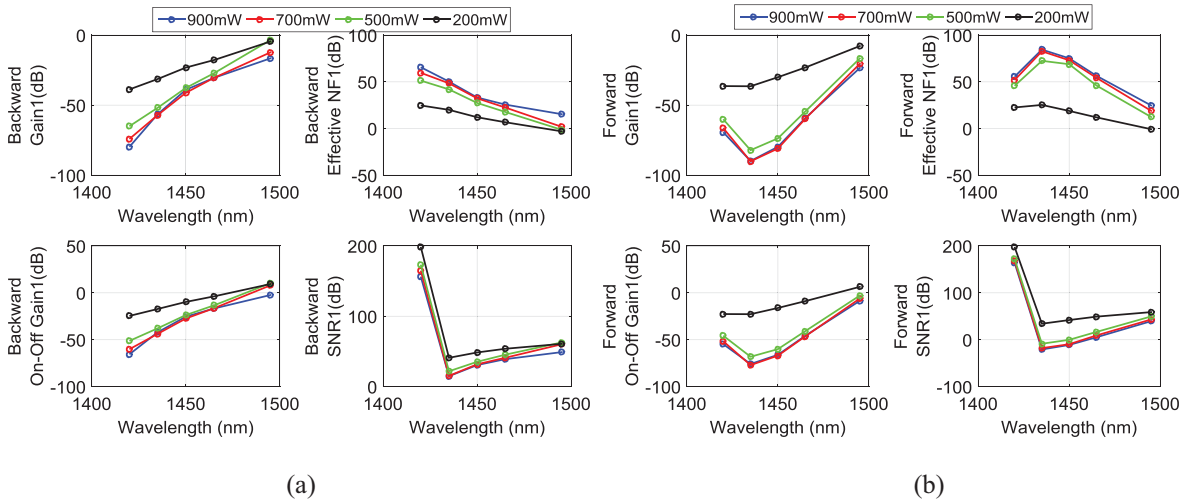
Figure 12: (a) SNR and gain plots for different pump power ratio in single forward and multiple backward bidirectional pumping (Wavelength Set-1). (b) SNR and gain plots for different pump power ratio in multiple forward and single backward bidirectional pumping (Wavelength Set-1).

Figure 13: Wavelength spectrum for bidirectional pumping.

Figure 14: (a) SNR and gain plots for different pump power ratio in single forward and multiple backward bidirectional pumping (Wavelength Set-2). (b) SNR and gain plots for different pump power ratio in multiple forward and single backward bidirectional pumping (Wavelength Set-2).
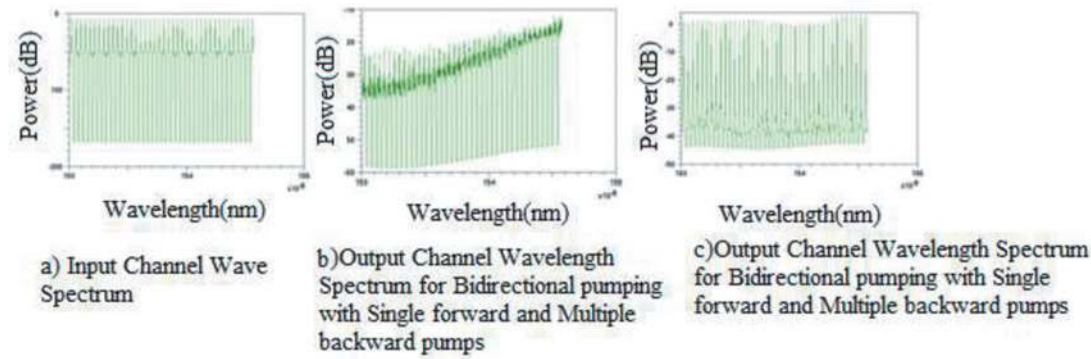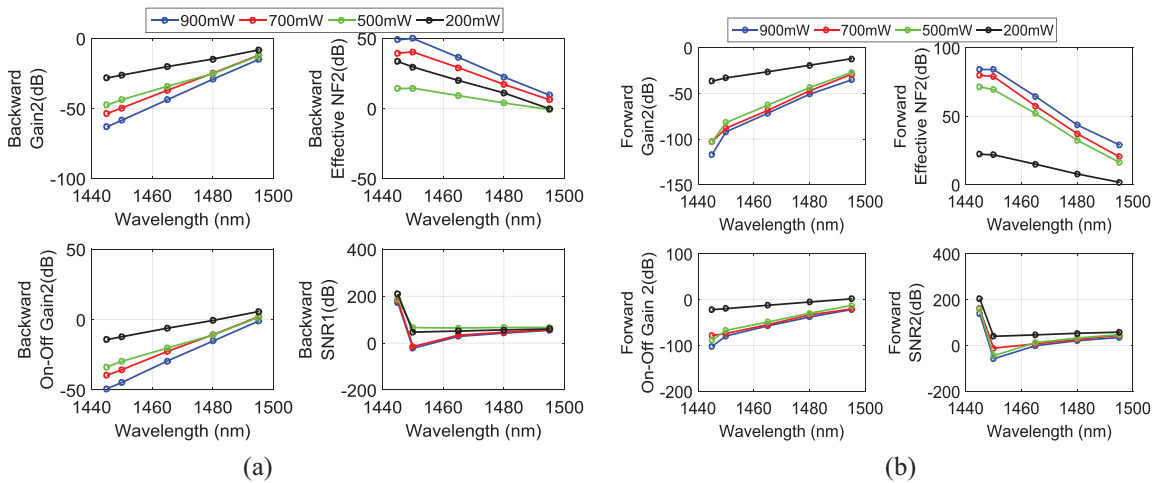
For the second set of wavelengths with single forward and multiple backward pumping (Figure 14(a) and 14(b) it was found that the forward absolute gain in the range of wavelength 1535–1555 nm is −0.04 dBm/GHz and forward gain is found to be 20.95 dB. Forward on-off gain is found as 35.06 dB. The forward effective noise figure is found as −2.03 dB and forward SNR 38.64 dB. With single backward pumping and multiple forward pumping it was found that the forward absolute gain in the range of wavelength 1535–1555 nm is −7.71 dBm/GHz and forward gain is found to be 13.37 dB. Forward on-off gain is 27.74 dB. The forward effective noise figure and forward SNR are −6.14 dB and 48.44 dB, respectively.

4 Conclusion

From the analysis presented in this paper it is found that as the number of pumps is increased, there is significant increase in gain and effective noise figure is also high. We have evaluated the different pumping methods with different sets of pump wavelength. From different pumping methods analysis, bidirectional pumping with more number of backward pumps or counter pumps gave most optimum gain as well as noise figure. Distributed Raman amplifiers can be used as booster amplifiers, pre amplifiers and inline amplifiers and according to each application, the requirement for gain and noise figure element is also different. It is also found that the pump power is more relevant during the first 50 km of the distributed fiber line and it is found decreasing as it goes beyond 100 km. So by choosing the optimum pumping methods and number of pumps, the Raman Amplifiers can be used in almost all places where optical amplifiers are required. Apart from single stage amplifiers analyzed above, dual stage distributed amplifiers and cascaded amplifiers can also use the same bidirectional pumping methods to improve their noise figure and gain.

References

1. Bromage J. Raman amplification for fiber communications systems. J Light Technol. 2004;22:79–93.
2. Mustafa FM, Khalaf AAM, Elgeldawy FA Multi-pumped Raman amplifier for long-haul UW WDM optical communication systems : gain flatness and bandwidth enhancements. In: 15th International Conference on Advanced Communications Technology (ICACT). 2013:122–7.
3. Matsuda T, Naka A. Operational issues facing commercial Raman amplifier system: safety measures and system designs. J Light Technol. 2016;34:484–90.
4. Olonkins S, Bobrovs V, Pilats D, Porins J Comparison of EDFA and LRA preamplifier performance in WDM transmission systems. In: Progress In Electromagnetic Research Symposium (PIERS). 2016:3778–82.
5. Namiki S, Emori Y. Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelength-division-multiplexed high-power laser diodes. IEEE J Sel Top Quantum Electron. 2001;7:3–16.
6. Muciaccia T, Gargano F, Passaro VMN. A TWDM-PON with advanced modulation techniques and a multi-pump Raman amplifier for cost-effective migration to future UDWDM-PONs. J Light Technol. 2015;33:2986–96.
7. Hansen PB, Eskildsen L, Grubb SG, Stentz AJ, Strasser TA, Judkins J, et al. Capacity upgrades of transmission systems by Raman amplification. IEEE Photonics Technol Lett. 1997;9:262–4.
8. Headley C, Agrawal GP. Raman amplification in fiber optical communication systems. Elsevier Academic Press, USA, 2005:374.
9. Ania Castanon J, Kobtsev SM, Pustovskikh A, Turitsyn SK. Simple design method for gain-flattened three-pump Raman amplifiers. Opt Quantum Electron. 2002;39:213–20.
10. Olsson NA. Lightwave systems with optical amplifiers. J Light Technol. 1989 July;7:1071.
11. Syuaib I, Asvial M, Rahardjo ET Ultra-long span optical transmission using bidirectional Raman amplification. In: International Conference on Quality in Research (QiR). 2015:86–9.
12. Kado S, Emori Y, Xamiki S, Tsukiji K, Yoshida J, Kimura T Broadband flat-noise Raman amplifier using low- noise bi-directionally pumping sources. In: 27th European Conference on Optical Communication. 2001:38–9.
13. Iqbal A, Martella GR, Gallazzi F, Tan M, Harper P, Ania-Castañón JD Performance improvement of broadband distributed Raman amplifier using bidirectional pumping with first and dual order forward pumps. In: 18th International Conference on Transparent Optical Networks (ICTON). 2016:8–11.
14. Ali MH, Abdullah F, Jamaludin MZ, Al-Mansoori MH, Ismail A, Abass AK Simulation and experimental validation of gain saturation in Raman fiber amplifier. 3rd Int Conf Photonics, Penang, 2012 October:27–29.
15. Haus H. The noise figure of optical amplifiers. Photonics Technol Lett IEEE. 1998;10:1602–04.
16. Agrawal GP. Fiber-optic communication systems. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2010.