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# Performance Analysis of Dual -Stage Raman Amplifier in Terms of Gain and Noise Figure

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## Abstract

This study determines the optimal configuration for dual-stage backward-pumped Raman fiber amplifiers to maximize gain and minimize noise figure in 1550 nm coherent transmission systems. A systematic numerical analysis was conducted using OptiSystem 7.0 software, comparing single-stage and dual-stage architectures. The methodology involved varying key parameters—pump power distribution from a 1480 nm laser source, Raman fiber length, and input signal power—within a fully loaded system framework. Critical simulation findings were validated through experimental measurements. The analysis identifies a dual-stage amplifier with 10 km per stage and an input signal power of -10 dBm as the optimal configuration. This design delivers superior gain flatness and a measurably lower noise figure than both single-stage designs and alternative dual-stage parameter sets. The result provides a concrete design guideline for developing high-performance Raman amplification systems in modern optical networks.

**Keywords:** Raman Amplifier, Noise Figure, Pump, Dual -Stage Raman Amplifier, Cascaded Raman Amplification, Optisystem Simulation**.**

## INTRODUCTION

Optical amplifiers are critical components of optical communication systems; they have evolved into an indispensable technology because they outperform other forms of amplifiers, such as Erbium-doped fiber amplifiers (EDFAs). The Raman amplifier (RA) is the most commonly utilized technology in commercial systems, and another popular fiber amplifier in long-haul systems (Hamaoka et al., 2019). Raman amplification is a distributed phenomenon in which signal amplification occurs within the transmission fiber. Fiber Raman amplifiers (FRAs) are now essential for 40-Gbit/s long-haul transmission and 10-Gbit/s ultra-long-haul transmission(Chen & Jiang, 2018). Raman amplifiers (RAs) offer several advantages, including decreased noise, a broad gain range for regulated gain profiles, and greater design flexibility to handle several wavelengths and modulation formats. One technique to developing the required form of signal power evolution is achieved by simultaneously adjusting the pump parameters using Raman amplifiers.

The signal power evolution in frequency and distance is a useful technique for improving some of the long-term objectives in optical communication systems, like signal-to-noise (SNR), in spectrum and spatial controlling. enhancement by improved signal quality, transmission distance and reduced fiber nonlinearity mitigates distortions, improving signal integrity(Hamaoka et al., 2019). These advantages make Raman amplifiers attractive for various applications, including long-haul optical communication systems, submarine communication cables; high-speed data center interconnects also optical sensing and imaging(Chen & Jiang, 2018).

The lack of uniformity is much more obvious in ultra-wideband systems due to the varied reactions and losses of optical components in different bands. In unrepeatered connection settings, RAs are crucial for delivering amplification from the receiver end; additionally, remote pumping and broad-band amplification utilizing RAs can be performed by deploying several Raman pumps of different frequencies(Li et al., 2013). However, due to the increased complexity of the problem, such arrangements make it difficult to optimize the pumps' frequency and power levels. This problem worsens when higher-order pumping is used.

Raman amplifiers are commonly classified as distributed counter pumps and co-pumps (Chen & Jiang, 2018). Raman amplifiers, whether lumped or discrete, use a long fiber spool for signal amplification. The DRA pump laser connects to the fiber span in a counter-pump or co-pump configuration. The counter pump architecture is recommended to avoid nonlinear distortions caused by large signal strengths at the beginning of the fiber span (Figure 1 (Li et al., 2013)).

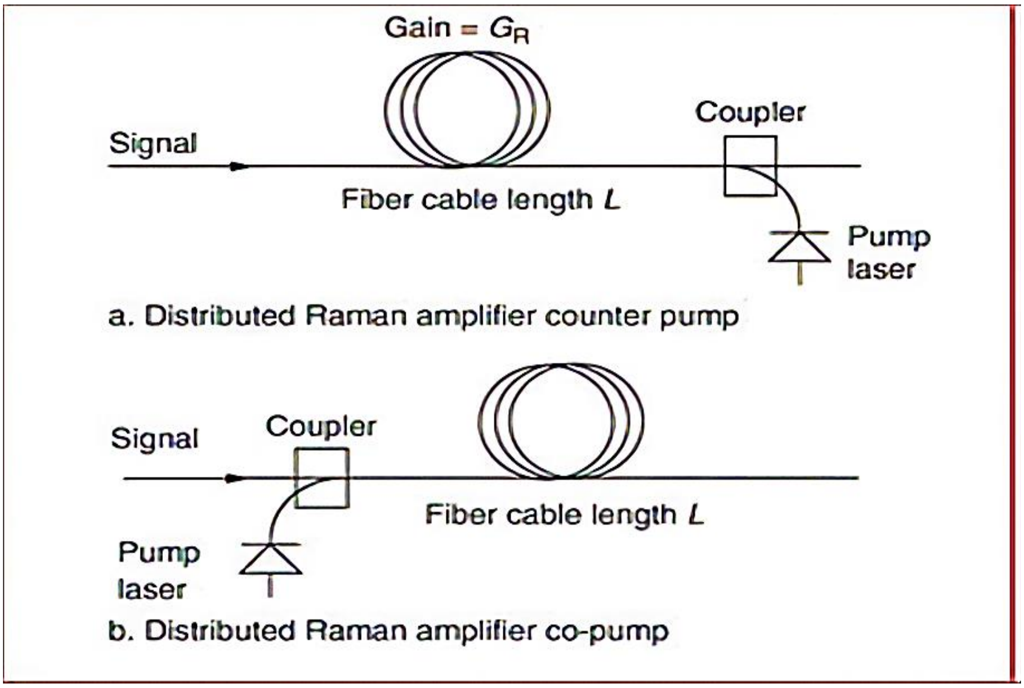


**Figure: (1).** Types of Raman amplifiers

Cascaded Raman amplification offers an advanced method utilizing Raman amplifiers (RAs). In optical communication systems, cascaded Raman amplification is used to increase the gain and range of Raman amplifiers. To obtain larger gain and extended reach, cascaded Raman amplification connects many Raman amplifiers in sequence, with the output of one amplifier feeding into the input of the next(Li et al., 2013). Cascaded Raman amplification provides various benefits compared to single-stage Raman amplification, such as: increased gain enabling longer transmission ranges, diminished noise resulting in an enhanced signal-to-noise ratio, and better performance by lessening the influence of nonlinear effects that can impair system efficiency(Yang et al., 2013). Many research studies have been carried out regarding the application of single-stage and multi-stage Raman amplifiers. Fathy M. Mustafa et al. Assesses cascaded two- and three-stage backward-pumped RAs across a distance of 100 km, attaining approximately 31 dB gain with a 600 mW pump in Truewave fiber (F. Mustafa et al., 2022). This study compares two cascaded models: a two-stage model (comprising a forward and a backward pump) and a three-stage model (featuring two forward pumps and one backward pump). The comparison is conducted across SMF, True-wave, and Freelight fibers over a distance of 100 km. The findings indicate substantial gain improvements, reaching up to approximately 46 dB at a pump power of 700 mW (F. M. Mustafa et al., 2023). An innovative study of cascaded Raman processes with multi-wavelength excitation, conducted through theoretical and experimental approaches. Shows that even with solely reverse pumping, distributing gain throughout stages leads to smoother gain profiles and a reduced noise figure (Jian Chen, 2006). introduced two cascaded backward-pumped Raman amplifiers to address gain attenuation over a distance of up to 80 km (F. Mustafa et al., 2022).

In this paper, an optical transmission model consisting of two cascaded Raman amplifiers equipped with a forward pump is proposed. This model is studied to determine the best overall gain and lowest noise with an optimal Raman amplifier length at different amplifier powers.

The paper is organized into. The fundamental model and analysis are demonstrated in Sec.2. The results obtained are presented and discussed in sect.3 using Optisystem 7 simulator. Sec.4 conclusion of the work.

## Raman Amplifier Working Principle:

Pump laser photons collide and are absorbed by fiber molecules or atoms as they pass through the fiber. As a result, the energy levels of the molecules or atoms increase. Since higher energy levels are unstable, they quickly decay to lower intermediate energy levels, which at lower frequencies release energy in the form of photons in any direction. This adds to the fiber's noise and is referred to as spontaneous Raman scattering or Stokes scattering (Soltani et al., 2022). The energy change is smaller than the initial energy received when the molecules were excited because they decay to an intermediate energy vibration level. The energy change from the excited to the intermediate levels, where $f = E / h$, determines the photon frequency (where h is Planck's constant, $h=6.62607\times10^{-34}$ J·s). This determines the form and location of the Raman gain-frequency curve and is referred to as the Stokes frequency shift. The fiber's phonons, or molecular vibrations, squander the remaining energy from the intermediate level to the ground level. The gain curve has a spectrum breadth of about 30 THz due to the large range of higher energy levels (Agrawal et al, 2012). Signal amplification occurs when signal photons propagate the frequency gain curve spectrum and absorb energy from the Stokes wave during stimulated Raman scattering.

## Modeling of Raman Amplifier

It is modeled using coupled ordinary differential equations (ODE) is resolved along the axis of iteration for faster convergence speed and equivalent accuracy(Soltani et al., 2022; Tan, 2018). Distributed (FRA) uses a lengthy length of transmission fiber is used as the gain medium, and the effects of amplified spontaneous emission (ASE) and Rayleigh scattering are neglected. therefore, the coupled nonlinear Raman processes between waves in the fiber may be stated as:

$$\mp\frac{dP_i}{d_z} = -\propto_i P_i + \sum_{j=1}^{M+N} g_{ji} P_j P_i \qquad (1)$$

Where $P_i$ is the power of the wave, αi is the attenuation coefficient, g is the Raman gain coefficient ($A_{eff}$) is the effective area (M, N) is the number of pumps and signal waves. After dividing equation (1) by $Pi$ and integrating over z (de O. Rocha et al., 2015).

$$P_i(z) = P_i(0)\ \exp\left[\pm\propto_i z \pm \left(\sum_{j=1}^{M+N} g_{ji} \int_0^z P_j(\xi) d\xi\right)\right] \qquad (2)$$

By adding additional integration process, we can obtain that:

$$\frac{\int_0^z P_i(\xi)d\xi}{P_i(0)} = \int_0^z exp\left[\pm\propto_i \xi \pm \left(\sum_{j=1}^{M+N} g_{ji}\int_0^z P_j(\xi)d\xi\right)\right]d\xi \quad (3)$$

Convert equation (3) into a closed integral according to $L_{eff}$ it becomes:

$$L_{eff_i}(z) = \int_0^z exp\left[\pm\propto_i \xi \pm \left(\sum_{j=1}^{M+N} g_{ji}(0)L_{eff_i}(\xi)\right)\right]d\xi \quad (4)$$

Then, solve the equation by applying iteration method to equation (4):

$$L^{(n)}_{eff_i}(z) = \int_0^z exp\left[\pm\propto_i \xi \pm \left(\sum_{j=1}^{M+N} g_{ji}P_j^{(n-1)}(0)L^{(n-1)}_{eff_j}(\xi)\right)\right]d\xi \quad (5)$$

To achievement putting the preceding equations into the numerical domain, we generate a vector $\mathrm{L}^{(n)}_{\mathrm{eff\_1}}(\overrightarrow{\mathrm{z_k}})$ to assign the value of $L_{eff}$at the ith wavelength at the position vector $Z_k$

$$L^{(n)}_{eff_i}(\overrightarrow{z_k}) = exp\left[\exp(\pm\propto_i \vec{z}_k \pm (\vec{g}_{ji}\vec{P}_j^{(n-1)}(0).\tilde{L}^{(n-1)}_{eff_j}(\vec{z}_k)\right].\tilde{T}_{trig}.\Delta z \quad (6)$$

Where:$\vec{z}_k = [0 \quad \Delta z \quad 2.\ \Delta z \quad 3.\Delta z \ \ldots \ L - \Delta z \quad L]$

$$L^{(n)}_{eff_i}(\vec{z}_k) = \left[L^{(n)}_{eff_i}(0)L^{(n)}_{eff_i}(\Delta z)L^{(n)}_{eff_i}(2\Delta z)\ldots L^{(n)}_{eff_i}(L)\right] \quad (7)$$

$$\overrightarrow{\vec{g}_{ji}\vec{P}_j^{(n-1)}}(0) = \left[g_{1i}P_1^{(n-1)}(0)g_{2i}P_2^{(n-1)}(0)g_{3i}P_3^{(n-1)}(0)\ \ldots\ g_{N+N_i}P^{(n-1)}_{M+N}(0)\right] \quad (8)$$

$$\tilde{L}^{(n-1)}_{eff_j}(\vec{z}_k) = \begin{bmatrix} L^{(n-1)}_{eff_1}(0)L^{(n-1)}_{eff_1}(\Delta z)L^{(n-1)}_{eff_1}(2\Delta z) & \ldots. & L^{(n-1)}_{eff_1}(L) \\ L^{(n-1)}_{eff_2}(0)L^{(n-1)}_{eff_2}(\Delta z)L^{(n-1)}_{eff_2}(2\Delta z) & \ldots & L^{(n-1)}_{eff_2}(L) \\ L^{(n-1)}_{eff_3}(0)L^{(n-1)}_{eff_3}(\Delta z)L^{(n-1)}_{eff_3}(2\Delta z) & \ldots & L^{(n-1)}_{eff_3}(L) \\ \vdots & \vdots & \vdots \\ L^{(n-1)}_{eff_{M+N}}(0)L^{(n-1)}_{eff_{M+N}}(\Delta z)L^{(n-1)}_{eff_{M+N}}(2\Delta z) & & L^{(n-1)}_{eff_{M+N}}(L) \end{bmatrix} \quad (9)$$

$$\widetilde{T}_{trig} = \begin{bmatrix} & 0 & \frac{1}{2}\frac{1}{2}\frac{1}{2} & & \cdots & \frac{1}{2} \\ 0 & \frac{1}{2} & 1 & 1 & \cdots & 1 \\ 0 & 0 & \frac{1}{2} & 1 & \cdots & 1 \\ 0 & 0 & 0 & \frac{1}{2} & \cdots & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \frac{1}{2} \end{bmatrix} \quad (10)$$

So, the gain (G) at a certain wavelength can be written as:

$$G_i = \sum_{j=1}^{M+N} g_{ji}.L_{eff_j}(L).P_j(0) \quad (11)$$

$P_j(0)$as vector elements we now change the gain equation (11) into this form:

$$\vec{G} = \tilde{T} \times \vec{P} \tag{12}$$

By the re-formulation of these equations, very precise prediction of pump powers, and quick generation of gain profiles are possible.

$$\overrightarrow{G}_{i=M+1\ldots N} = \sum_{j=1}^{M+N} g_{ji}.L_{eff_{-j}}(L).P_j(0), \quad \vec{G}_s = \tilde{T}_P \times \vec{P}_P + \tilde{T}_s \times \vec{P}_s \tag{13}$$

## RESULTS AND DISCUSSION

Our proposed model gives relationship between the optimal pump laser power, Raman amplifier length, through the factors gain, and noise figure in C-band are simulated by Optisystemv.7. The main parameters utilized for this simulation are presented in Table1.

**Table:(1).** Simulation parameter

| Parameter | Value |
|---|---|
| Amplifier length | (10-70) km |
| Pump power | (1000-1900) nm |
| Signal wavelength | 1550 nm |
| Pumping wavelength | 1480 nm |
| Power of CW laser | -10 dBm |

### Effect of Pump of Power on Gain and Noise Figure at Single Stage

The initial evaluation stage is to train and evaluate the Raman model, which was created using a single wavelength source (1550 nm) with randomly selected pump powers, a 1480 nm pump wavelength for forward pumping, and pump power ranging from 1000 mW to 1900 mW. Figure 2 shows an illustration of the suggested model. The parameters Gain and Noise figure depicts the signal power (-10 dBm) measured at various distances from the Raman amplifier (10-30-50-70 km).

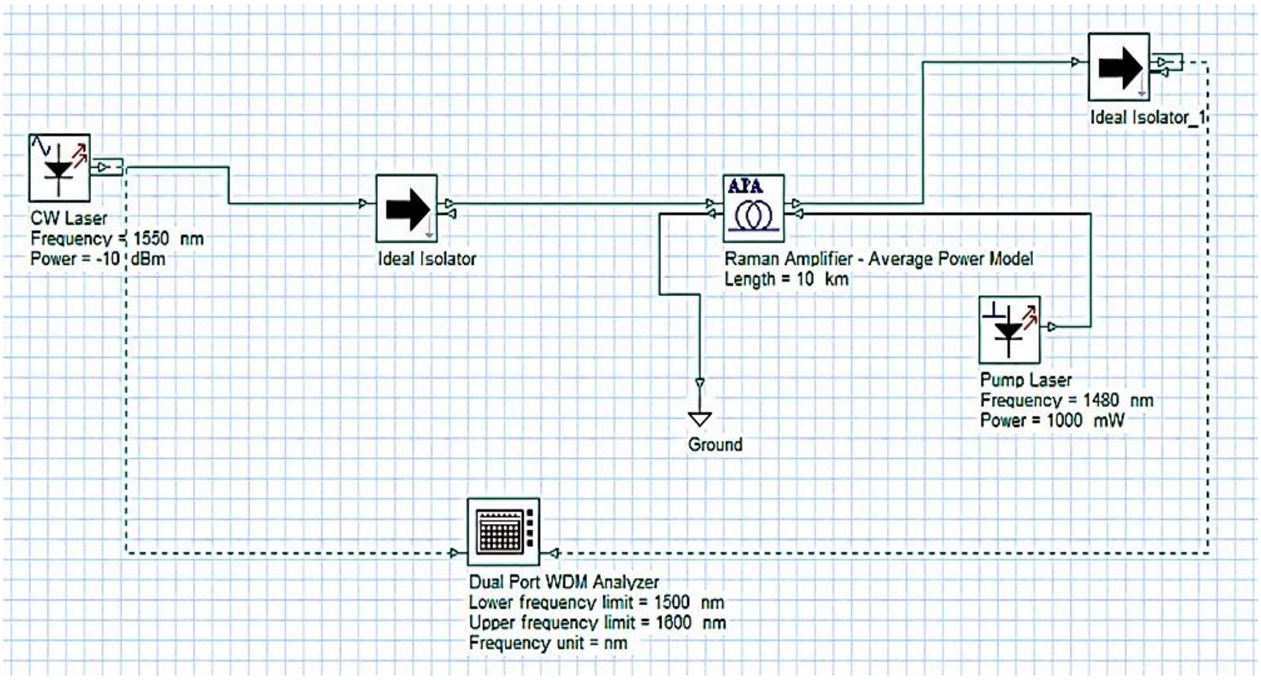


**Figure: (2).** Single Stage Raman optical amplifier design using scheme of the backward pumping.

Figure 3 displays the Raman amplifier performance for the forward pumping pump in terms of the active length of the Raman and the expected pump power values. The gain increases with increasing pump power from 1000 to 1900 mW and fiber length, reaching a maximum value of 25 dB at 30 km, where the gain distribution is at its best. Thereafter, the gain decreases to 18 dB at 70 km. increasing fiber length with increasing pump power results in increased ASE noise and nonlinear effects, and thus an increase in NF.

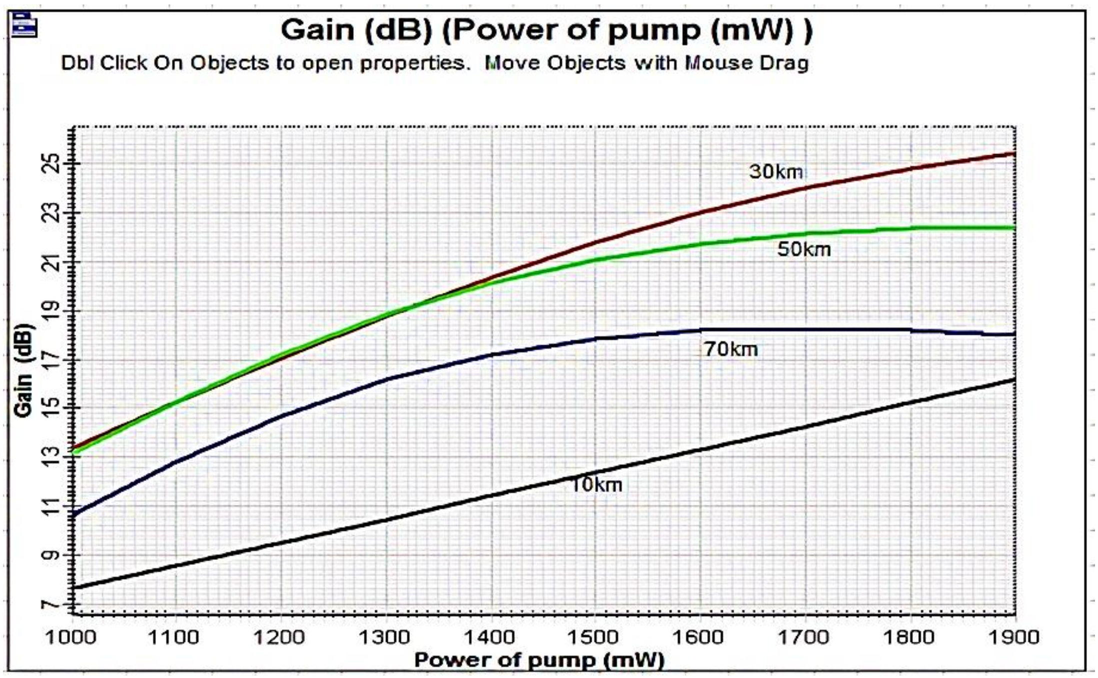


**Figure: (3).** Variation of gain at single stage with different Raman amplifier lengths and different power

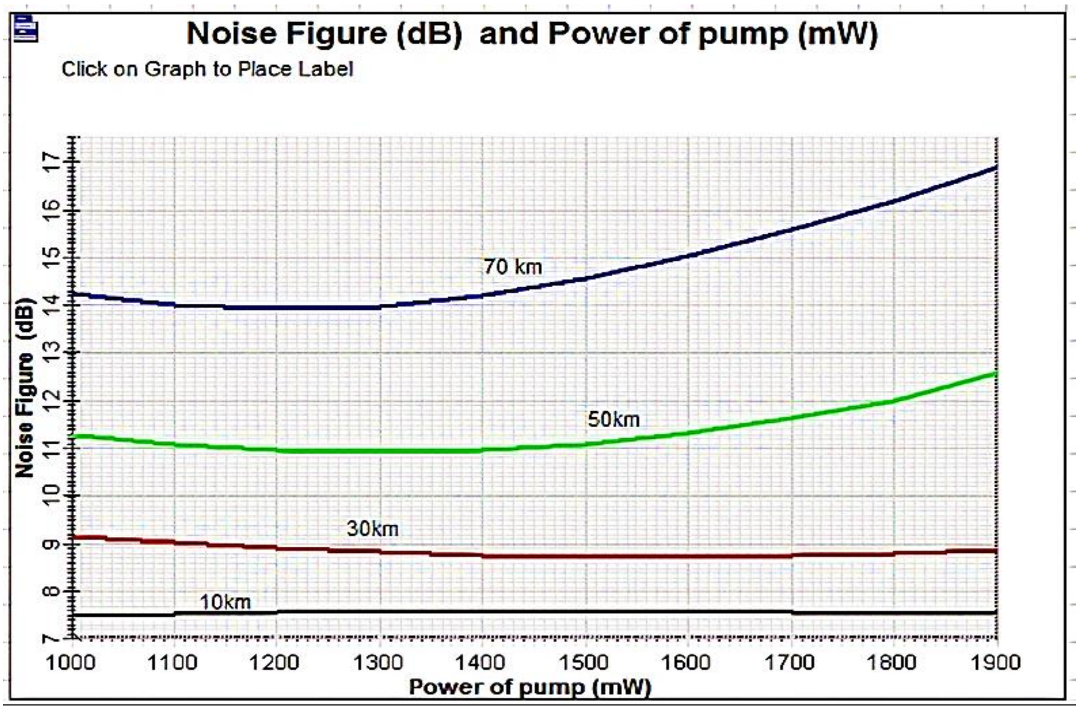


**Figure: (4).** Changes in the noise figure at single stage with various Raman amplifier lengths and variations power pump ($\lambda_P$ =1480 nm)

Because it has little effect on the signal profile, the noise figure is large for low pump power values and a Raman length of 30 km (see Figure 4). Pump power becomes increasingly significant as it rises. various subsets ranging in length from 10-30-50-70 km. examined in order to train the gain and assess the accuracy of the generated validation set. These analyses lead to the selection of 30 km as the Raman amplifier's final training length at a wavelength pump of 1900 nm.

**Effect of Pump Power on Gain and Noise Figure at Dual-Stage**

This section looks at experiments using a two-stage amplifier. Two Raman amplifiers are connected in cascade via an isolator. Figure 5 depicts the schematic diagram for the two Raman amplifiers. The input is a single wavelength source at 1550 nm with a power of -10 dBm. The first stage features a forward pump source and a separate power pump (ranging from 1000 mW to 1900 mW) at 1480 nm, as well as a 10-kilometer fiber length. The input signal for the second stage is the output signal from the first stage, and lengths of 10 km for the second stage are studied using the same pump characteristics as the first stage.

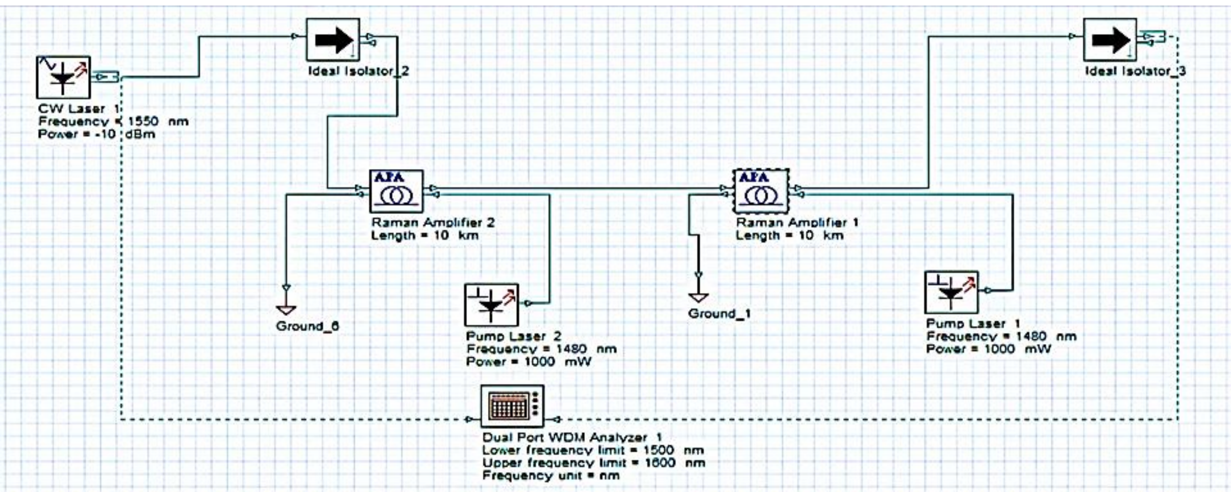


**Figure: (5).** dual-Stage Raman optical amplifier design using scheme of the backward pumping

Figure 6 indicates hence the first- and second-stage amplifiers' maximum gain at the ideal length of the Raman amplifier is 28.93 dB; the first and second-stage amplifiers' maximum gains added together represent the maximum gain for the entire system.

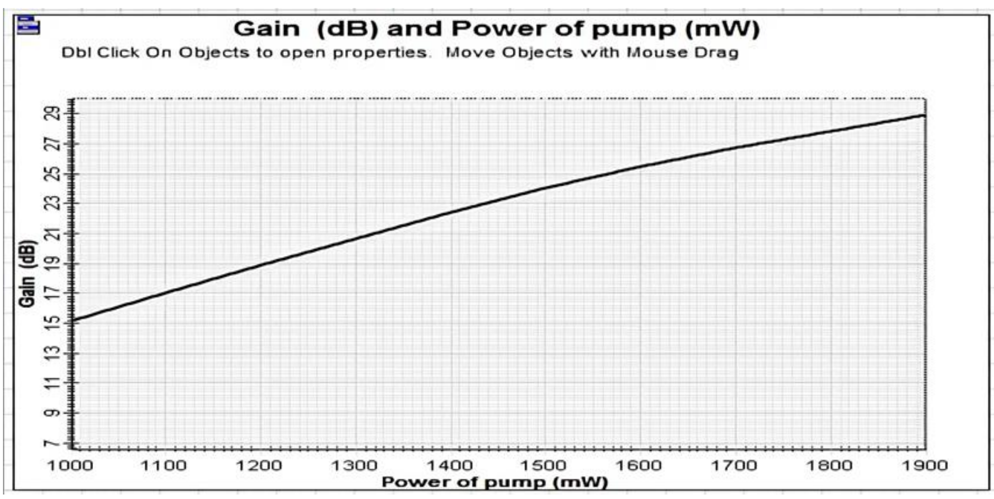


**Figure: (6).** Changes in Gain at dual-stage with Raman amplifier length (30km) and different power.

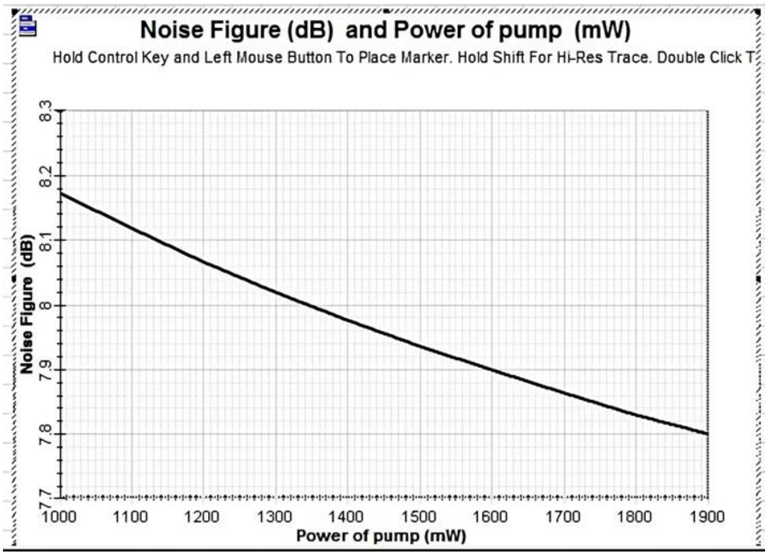


**Figure: (7).** Variation of noise figure at dual-stage with (30km) and different power

The essential feature of a two-stage amplifier is that it shortens a major amount of the fiber's length, allowing gain to increase at the price of length and lowering the noise figure, as shown in Figure 7. As shown in Table 2, the optimal length of the Raman amplifier in the first- and second-stage amplifiers is 10 km, and the signal power is -10 dBm when comparing and analyzing the gain and noise figure using a single-stage Raman amplifier and a two-stage Raman amplifier at the signal wavelength source (1550 nm), with a pump source of 1480 nm wavelength and a power pump of 1900 mW. According to Table 2, the single-stage Raman amplifier's gain is 25.43 dB, while Figure 8 illustrates that the two-stage Raman amplifier's gain is 28.93 dB.

**Table:(2).** Comparison of single-stage and two-stage Raman amplifiers' maximum gain and noise figure

| Types of Raman Stricture | Max Gain(dB) | Noise Figure(dB) |
|---|---|---|
| Single stage | 25.43 | 8.88 |
| Dual stage | 28.93 | 7.79 |

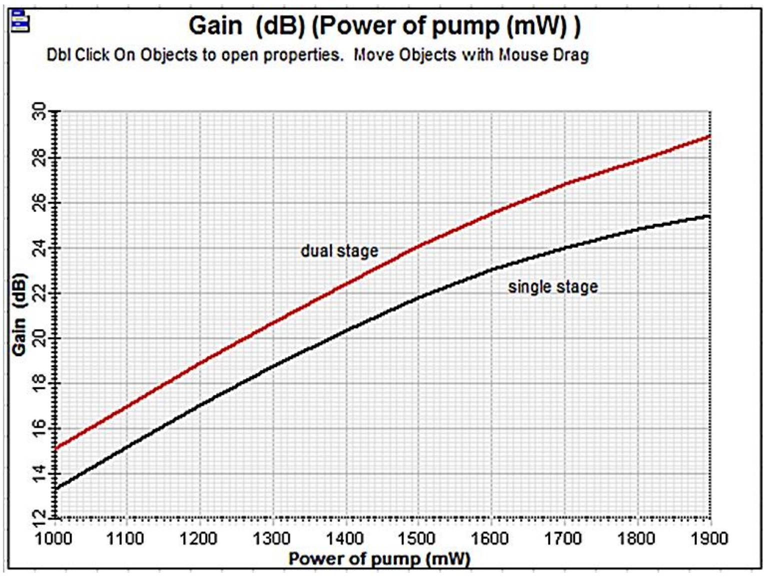


**Figure: (8).** Variation of Gain with length of Raman amplifier at 30 km for single stage and dual stages.

Figure 9 illustrates how the two-stage Raman amplifier increases the signal gain by 3.50 dB with a straightforward adjustment in Noise Figure.

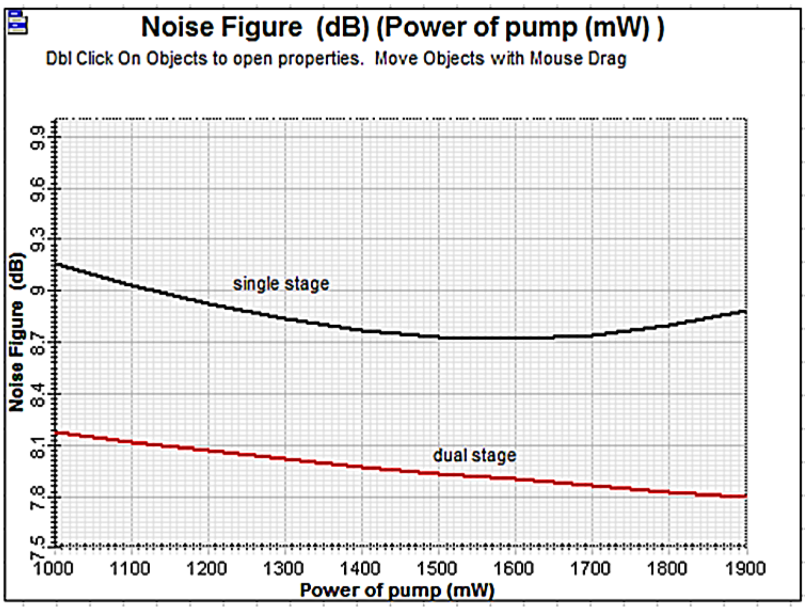


**Figure: (9).** Variation of Noise figure with length of Raman amplifier at 30 km for single stage and dual stages.

The second stage serves as a power amplifier, increasing the signal's strength. The ideal length of the second stage Raman amplifier is 10 km. Our method increases system performance at 1550 nm by adjusting pump powers; thereafter, the lengths of Raman amplifiers 1 and 2 are set at 10 km. better performance and cheaper manufacturing costs are accomplished by lowering the Raman amplifier length by 20 km for each amplifier individually and 10 km for both amplifiers combined, as opposed to the 30 km Raman amplifier length used in single stages.

## CONCLUSION

This study has presented the performance analysis of a two-stage active multi-length Raman amplifier in order to enhance gain and noise characteristics by the OptiSystem simulator. Significant gains in system gain and noise characteristics were achieved by carefully optimizing the amplifier architecture, considering the active fiber's length and the power distribution from several pumps. A forward pump and two cascaded Raman amplifiers make up the multistage suggested concept. The model is tested at various power pump (1000-1900 mw) and amplifier lengths to achieve the optimum overall gain and the lowest noise figure. Comparing the results achieved between the single and dual stages. The most favorable gain, 28.93 dB, is acquired at the same pump power, 1900 mW, with a shorter Raman amplifier, 20 km, and a noise figure of 8.88 dB at the dual-stage Raman amplifier compared with the single-stage that achieved a gain of 25.43 dB with a Raman length of 30 km. Although the single-stage 30 km amplifier produces a moderate gain, the length of the fiber causes a large build-up of amplified spontaneous emission (ASE), increases noise Figure, and distributes gain unevenly throughout the fiber. By distributing amplification over shorter fiber sections, the multistage 10 km configuration, on the other hand, produces a higher and more consistent gain, effectively suppresses noise, lowers ASE accumulation, and permits more effective pump utilization. With these enhancements, the two-stage Raman amplifier architecture offers a satisfactory trade-off between gain, noise performance, and system scalability, making it an excellent choice for extended distances and high-capacity systems that use optical communication.

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