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Enhanced gain Raman amplifiers using different pumping schemes

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Abstract

Raman amplifiers (RAs) can be represented as one of the best solutions for transmission techniques, where they can compensate attenuation and transmit the optical signal to long-haul distances. This work proposes and investigates two cascaded models (multi-stages of RAs) for enhancing the received power and the overall gain. This study includes three fiber types: Dispersion Shifted Fiber, Truewave and Freelight fibers at 100 km distance and pumping powers of 500, 600 and 700 mW. The obtained results reveal that the best results gain is 46.46 dB and the power of output signal is 42.47 dBm achieved at 700 mW pump power with Truewave fiber. The models are compared with previously published work, where the gain and the output signal power are enhanced to more than 66.58–85.84%.

Keywords Raman amplifier · Pumping power · Amplifier gain · Received signal power

1 Introduction

In optical fiber communication systems, loss refers to the reduction in the intensity of the optical signal as it propagates through the fiber. This loss is primarily due to absorption and scattering. Absorption occurs when the photons in the optical signal are absorbed by the material comprising the fiber. This can be due to impurities or defects in the fiber material

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(Agrawal et al. 2012). The absorption loss is typically higher at shorter wavelengths. Scattering occurs when the photons in the optical signal are scattered in different directions as they pass through the fiber. This can be due to microscopic variations in the refractive index of the fiber material, or due to impurities or defects. The scattering loss is typically higher at longer wavelengths (Keiser et al. 2021).

The loss problem can be overcome by optical fiber amplifiers which amplify optical signals without the need for electrical regeneration. The amplification is achieved due to the stimulated emission of photons from the dopant atoms in the fiber, which amplifies the signal. There are several types of optical fiber amplifiers (Singh et al. 2019) (1) Erbium Doped Fiber Amplifier (EDFA) which is the most common type of optical fiber amplifiers and is used in long-haul communication systems. It amplifies signals in the 1530–1620 nm wavelength range, which is the most commonly used range for optical communication, (2) Raman amplifiers which use the Raman effect to amplify the signal. It can provide amplification over a wider range of wavelengths, and (3) Semiconductor Optical Amplifiers (SOA) which uses a semiconductor material to amplify the signal (Kilinçarslan et al. 2023). This is often used in short-haul communication systems and can provide high gain but suffers from nonlinear effects (Senior et al. 2009).

Raman amplifiers (RAs) offer several advantages over EDFAs and SOAs, including broadband amplification, lower noise, higher power handling capacity, and lower temperature dependence. However, EDFAs is still the most commonly used type of optical fiber amplifiers due to its simplicity, lower cost, and ease of integration into communication systems (Mahran et al. 2015). The choice of amplifier depends on the specific requirements of the application, and a combination of different types of amplifiers may be used to achieve optimal system performance (Hasan et al. 2013).

Raman amplification is providing a way to amplify signals over a wide range of wavelengths and is enabling high-quality, long-distance communication without the need for electrical regeneration (Souza et al. 2022). In Raman operation, the input signal is launched into the fiber and travels down its length. The pump laser is launched into the fiber at a slightly different wavelength than the signal. The difference in wavelength between the pump and signal is called the Raman shift (Headley et al. 2005). As the pump and signal travel down the fiber together as a forward pump or counter as a backward, the pump transfers energy to the signal through the Raman effect (Prakash et al. 2022).

Raman amplifiers (RAs) can be used in an enhanced approach as a cascaded Raman amplification. Cascaded Raman amplification is a technique used to further increase the gain and extend the reach of Raman amplifiers in optical communication systems. In cascaded Raman amplification, multiple Raman amplifiers are connected in series, with the output of one amplifier feeding into the input of the next, to provide higher gain and longer reach (Li et al. 2013). Cascaded Raman amplification offers several advantages over single-stage Raman amplification, including: higher gain which allows longer transmission distances, reduced noise which leads to a higher signal-to-noise ratio and improved performance by reducing the impact of nonlinear effects, which can degrade system performance (Yang et al. 2013). Several studies have been conducted on the use of single-stage and multistage Raman amplifiers with various pump power levels and fiber types, such as Single Mode Fiber (SMF), Freelight, and Truewave fibers. Saber et al. proposed a cascaded two-stage RA employing forward and backward pumps up to 100 km for various pump power levels and fiber kinds to increase gain (Saber et al. 2019). They also simulated and compared the parameters affecting Raman gain. Eman Salah et al. investigated the Raman gain and output signal power of a single Raman amplifier over a distance of 100 km with different pump powers and fiber types (Eman Salah et al. 2019). Fathy et al. used a backward pump with a Raman amplifier and observed the effects of gain-affecting parameters at different pump powers and fiber types (Mustafa et al. 2019). Finally, Mohamed Fayez et al. presented two cascaded backward pumped Raman amplifiers to overcome gain attenuation up to a distance of 80 km (Mohamed Fayez et al. 2022). Different backward pump levels and three different types of fiber are employed in the first and second RAs. The same settings are used to mimic the overall gain and signal power.

The two proposed models are explained as follows. The first model involves cascading two RAs; one with a forward pump and the other with a backward pump. The second model comprises three cascaded Raman amplifiers, with the first two having a forward pump and the third having a backward pump. These models are investigated to determine which one provides the best overall gain and output signal power at a distance of 100 km, using three different types of fibers: DSF, Truewave, and Freelight fibers. The models can also be used in long haul transmission distances and easy to fabricate as (Zhixian Li et al 2023).

The rest of this article is organized as follows. The basic model and analysis are illustrated in Sect. 2. Section 3 describes the proposed. The obtained results are displayed and discussed in Sect. 4 using Matlab simulation. Section 5 evaluates the proposed model. Section 6 concludes the work.

2 Analysis

Here, we outline the elements, ideas, and equations of operation for a distributed forward and backward pumped RAs. Figures 1 and 2 illustrate the system block diagrams for both RAs.

The detailed components are represented in Figs. 3 and 4. The components of the system are an optical fiber, an optical pump, and a coupler. In the opposite direction of the input optical signal, the optical pump power is linked into the optical fiber. Stimulated Brillouin Scattering (SBS) is induced through the optical fiber by the pumping power. The optical weak signal power from the pump is transferred to that of the optical signal, which is amplified as it travels through the effective section at the fiber end. Through the coupler, the boosted signal is transmitted to the receiver (Abd Elbaki et al. 2019, Beshr et al. 2020, Salah et al. 2014).

The differential equations that describe the conversion of pump power to signal power as well as signal and pump power attenuation due to propagation are (M. Fayez et al. 2022, Nihal et al. 2010, Abd El–Naser et al. 2012).

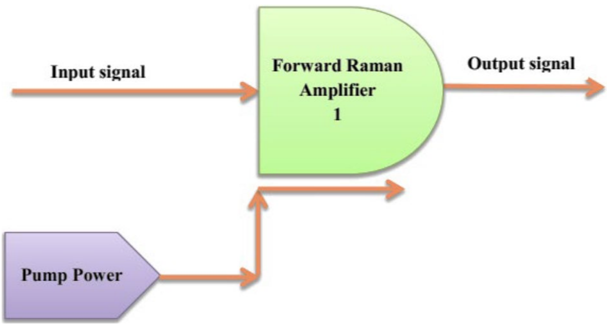

Fig. 1 Block diagram of a forward pumped RA

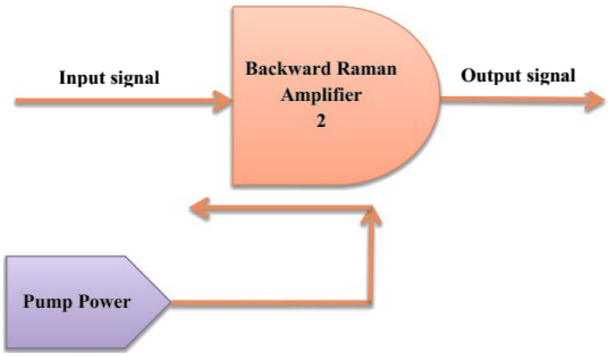

Fig. 2 Block diagram of a backward pumped RA

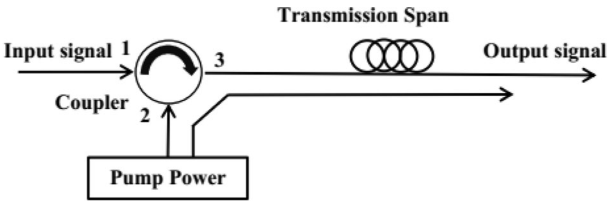

Fig. 3 RA forward pumped system (Salah et al. 2014)

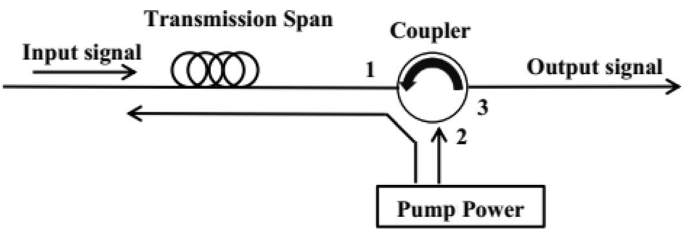

Fig. 4 RA backward pumped system (Abd Elbaki et al. 2019)

$$\pm\frac{\partial P_r}{\partial Z} = -\frac{\omega_r}{\omega_i} G_R P_r P_i - \alpha_r P_r \tag{1}$$

$$\frac{\partial P_i}{\partial Z} = G_R P_r P_i - \alpha_i P_i \tag{2}$$

where P_i and P_r are the signal and pump powers, respectively, G_R is the gain coefficient (W^{-1} m^{-1}), and Z is the propagation distance. The optical power for the signal and the pump is related to the attenuation coefficients α_i and α_r, respectively. The optical signal's and the pumping power's corresponding angular frequencies are ω_i and ω_r, respectively (Jyoti and Gupta 2014, Parul et al. 2014).

Equation (1) can therefore be solved by integrating both sides. If we are utilizing forward pumping (S = 1), one can write the pump power down as

$$P_r(Z) = P_r(0) \cdot e^{-\alpha_r L} \tag{3}$$

where $P_r(0)$ is the value of the pump power at point $Z=0$.

In the backward pumping case ($S=0$), the pump power is

$$P_r(Z) = P_r(0) \cdot e^{-\alpha_r(L-Z)} \tag{4}$$

In the general case, when a bidirectional pumping is used ($S=0$ or 1), the laser sources work at the same wavelength and at different pump powers. Therefore, to calculate the pump power at z, one uses

$$P_r(Z) = SP_r(0) \cdot e^{-\alpha_r L} + (1 - S)P_r(0) \cdot e^{-\alpha_r(L-Z)} \tag{5}$$

The signal power at the forward and backward pumps can be provided by Eq. (2) if the pump power is replaced and ranges from 0 to L as (Parul et al. 2014, Mustafa et al. 2019)

$$P_i(Z) = P_i(0) \cdot e^{\left(G_R P_0\left(\frac{(1-\exp(-\alpha_r Z))}{\alpha_r}\right)-\alpha_i Z\right)} = G_F \cdot P_i(0) \tag{6}$$

$$P_i(Z) = P_i(0) \cdot e^{\left(G_R P_0\left(\frac{\exp(-\alpha_r L)(1-\exp(-\alpha_r Z))}{\alpha_r}\right)-\alpha_i Z\right)} = G_B \cdot P_{i_s}(0) \tag{7}$$

where $P_r(0)$ represents the pump power at the position $Z=0$ and gains G_F and G_B, respectively, correspond to forward and backward pumped amplifiers, respectively, $P_r(0)$ is the value of the pump power at point $Z=0$. The expression for the linear signal and pump energy attenuation coefficients in optical fibers is

$$\alpha_i = \alpha_r = \alpha/4.343 \tag{8}$$

α (dB/km) here is the attenuation coefficient.

3 Proposed Model

The two proposed schemes are: first one (proposal one) is two cascaded RAs; one of them is backward pumped and the other is a forward pumped. The second one (proposal two) is three cascaded RAs; one is backward pumped and two are forward pumped. Each of schemes is separately modelled with its connections and governing equations.

3.1 Proposal one (two cascaded RAs)

Figure 5 illustrates the block diagram of this scheme.

Figure 6 illustrates the detailed connection for this model. To increase the overall gain, the output of the first forward pumped amplifier is coupled to the input of the second amplifier, which receives the output signal from the second RA.

By using two RAs pulsed in a cascaded form to increase the Raman gain, which can be stated as, Eqs. (6) and (7) might be used to generate the total gain of the two cascaded RAs (E. Salah et al. 2020)

$$G_T = G_f \times G_b \tag{9}$$

where G_T is the overall gain, G_f and G_b are, respectively the gain of forward and backward pumped RAs.

Then, using Eq. (9)

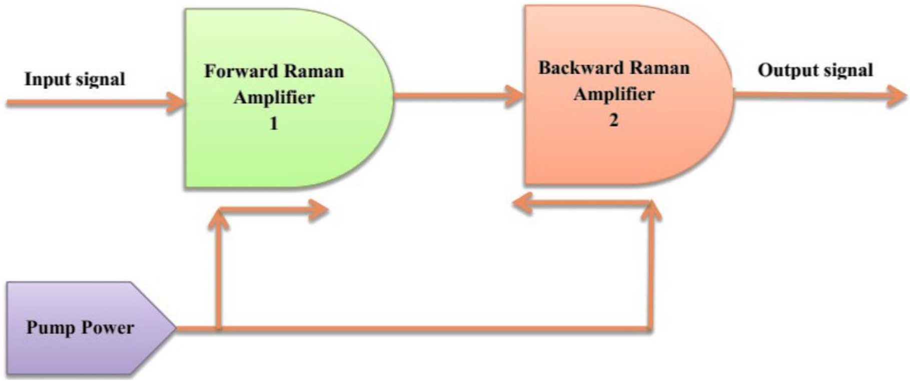

Fig. 5 Proposal one (two cascaded RAs)

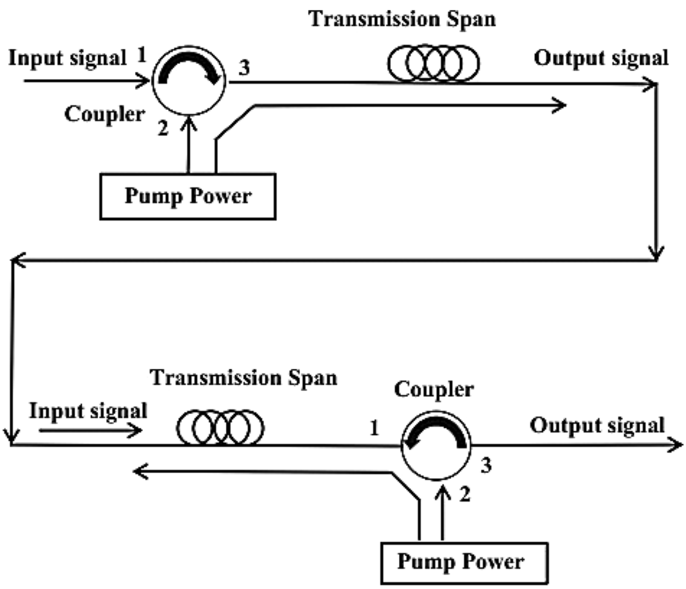

Fig. 6 Design model proposal one

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right)\left(\exp\left(\alpha_r z\right) - 1\right)}{\alpha_r} - \alpha_i Z\right] \times exp\left[g_R P_0 \times \frac{1 - \exp\left(-\alpha_r z\right)}{\alpha_r} - \alpha_i Z\right] \tag{10}$$

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right)\left(\exp\left(\alpha_r z\right) - 1\right)}{\alpha_r} + g_R P_0 \times \frac{1 - \exp\left(-\alpha_r z\right)}{\alpha_r} - 2\alpha_i Z\right] \tag{11}$$

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right) \cdot \exp\left(\alpha_r z\right) - \exp\left(-\alpha_r L\right) - \exp\left(-\alpha_r z\right) + 1}{\alpha_r} - 2\alpha_i Z\right] \tag{12}$$

At the amplifier output, the signal power is obtained by (Al-Alimi et al. 2017)

$$P_i(L) = P_i(0) \exp\left(\frac{g_0 P_0 L}{A_{eff}} - \alpha_i L\right) \tag{13}$$

where, $P_i(L)$ is the value of the signal power at point $Z = L$ and $P_i(0)$ is the value of the signal power at point $Z = 0$.

The effective length, abbreviated L_{eff}, is the length at which the SRS, or nonlinear effect, still appears in optical fibers, and is given by (Beshr et al. 2020)

$$L_{eff} = \frac{1 - \exp\left(-\alpha_r L\right)}{\alpha_r} \tag{14}$$

The amplifier gain is defined by the signal power ratio, with or without Raman amplification, and is thus determined by

$$G_A = \frac{P_i}{P_i(0) \exp\left(-\alpha_i L\right)} \tag{15}$$

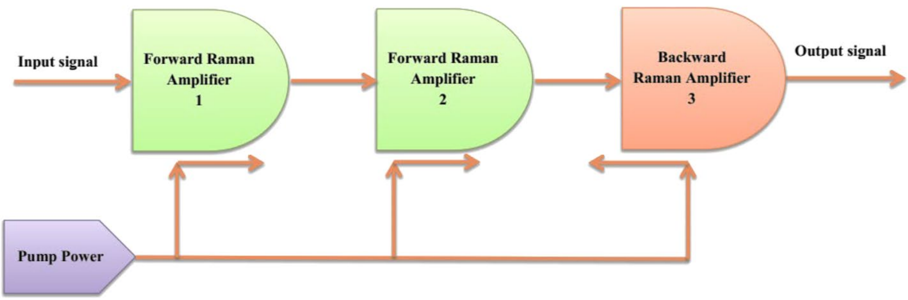

Fig. 7 Proposal two (three cascaded RAs)

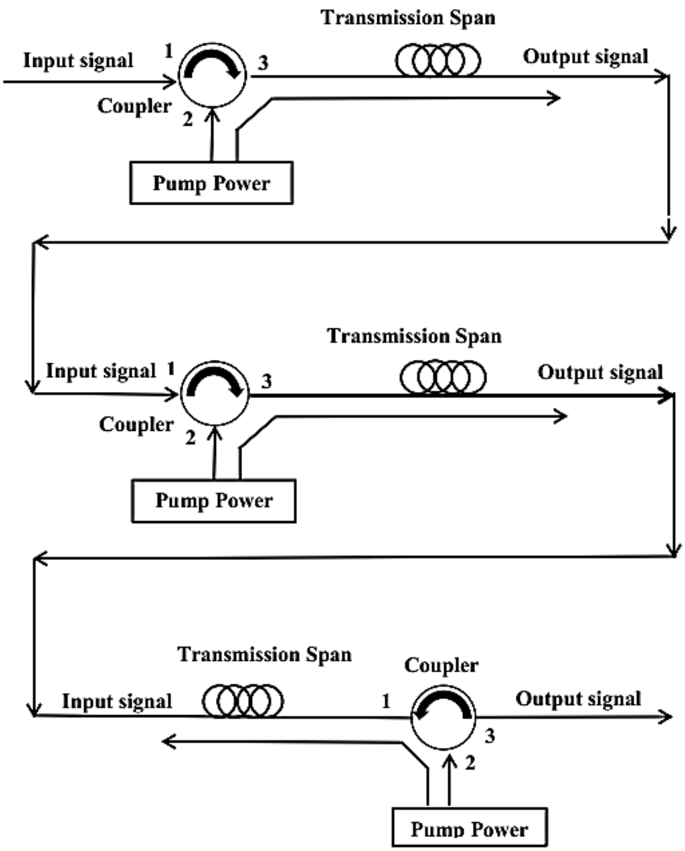

Fig. 8 Design model of proposal two

3.2 Proposal two (three cascaded RAs)

Here, three RAs are cascaded; each of them has its own pumping power as shown in Figs. 7 and 8.

For n cascaded RAs, the overall gain, G_T, can be obtained through Eqs. (6) and (7) as

$$G_T = G_b \times \prod_{i=1}^{n} Gf_i \tag{16}$$

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right)\left(\exp\left(\alpha_r z\right) - 1\right)}{\alpha_r} - \alpha_i Z\right] \times \prod_{i=1}^{n} exp\left[i \times \left(g_R P_0 \times \frac{1 - \exp\left(-\alpha_r L\right)}{\alpha_r} - \alpha_i Z\right)\right]_i \tag{17}$$

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right)\left(\exp\left(\alpha_r z\right) - 1\right)}{\alpha_r} -\alpha_i Z + \sum_{i=1}^{n} i \times [g_R P_0 \times \frac{1 - \exp\left(-\alpha_r L\right)}{\alpha_r} - \alpha_i Z]_i \right] \tag{18}$$

For the same fiber type and same length and only one forward amplifier (i = 1), then

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right).\exp\left(\alpha_r z\right) - 2\exp\left(-\alpha_r L\right) + 1}{\alpha_r} - 2\alpha_i Z \right] \tag{19}$$

The two cascaded RAs are one backward pumped and the other is forward pumped, with an overall gain G_T.

For the three cascaded RAs, one is a backward pumped RA and two are forward pumped RAs (i = 2), the overall gain is

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right).\exp\left(\alpha_r z\right) - 3\exp\left(-\alpha_r L\right) + 2}{\alpha_r} - 2\alpha_i Z \right] \tag{20}$$

In general, for i = n, then

$$G_T = exp\left[g_R P_0 \times \frac{\exp\left(-\alpha_r L\right).\exp\left(\alpha_r z\right) - (n+1)\exp\left(-\alpha_r L\right) + n}{\alpha_r} - 2\alpha_i Z \right] \tag{21}$$

Here, for n units of cascaded RAs; one backward pumped and (n − 1) forward pumped RAs, the overall gain is G_T.

4 Results and discussion

For the three models; basic model, proposal one, and proposal two, the relationships between the overall gain and the output received power with the fiber length are discussed. The mentioned relations are not only under the effect of different DSF, Freelight and True-wave fibers but also various pump power levels 500, 600 and 700 mW. The referenced work uses 800 and 900 mW pump powers to enhance the gain. In our work, we try to enhance the gain with pump powers lower than that mentioned in the referenced work to reduce the system powers and reduce the nonlinear effects at the same time. This is our motivation for choosing 500, 600 and 700 mW pump powers.

4.1 Raman gain versus fiber length at different pump powers

This section illustrates, at various pumping powers: 500, 600 and 700 mW, the relationship between overall gain and fiber length. Three types of fiber DSF, Truewave, and Freelight are used with the basic model and proposed models. The mentioned relations are illustrated in Fig. 9a, b, c.

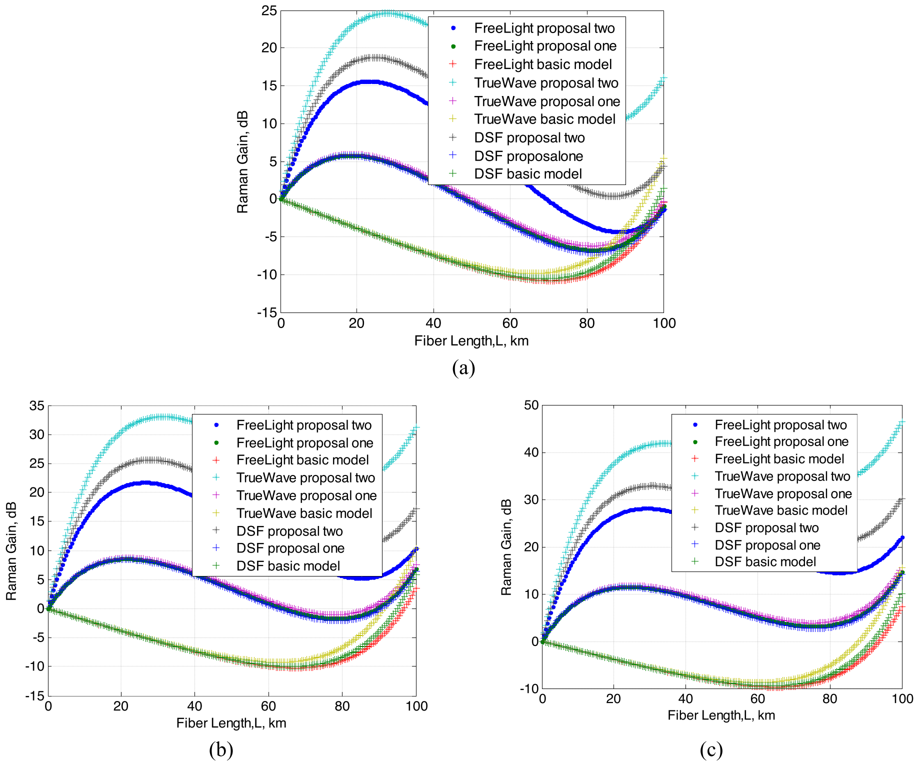

Fig. 9 Raman gain versus fiber length for different types of fiber at **a** 500, **b** 600 and **c** 700 mW pumping power: for basic and proposed models

4.1.1 Raman gain versus fiber length at pump power at 500 mW

Figure 9a shows this relation at pump power 500 mW. For proposal two, the gain increases sharply according to the effect of two cascaded forward pumped RAs to its maximum peak for all fiber types between distances 20 and 30 km, where Truewave fiber has the maximum gain of 25 dB. After that, the gain decreases gradually to its minimum between distances 80 and 90 km, where the lowest gain is less than zero for the Freelight fiber (which means a loss). Finally, due to the backward pump of the third RA, the gain increases again to 4.4 dB for DSF, 0 dB for Freelight and 16 dB for the Truewave fiber at 100 km.

For proposal one, due one stage only forward RA, the gain increases significantly to its maximum peak at distance 20 km, where the maximum gain for all fibers is close to each other. Then, it gradually decreases to its minimum less than zero level gain at 80 km. Due to the effect of the second cascaded backward Raman pump, the gain increases to 2.93, 0, 10.7 dB for DSF, Freelight and Truewave fibers, respectively at 100 km. For the basic model, the gain decreases gradually to its minimum peak at distance 70 km. It begins to rise as a result of the backward pump to 1.46 dB for DSF, 0 dB Freelight and 5.34 dB for Truewave at 100 km.

4.1.2 Raman gain versus fiber length at pump power at 600 mW

By increasing the pump power to 600 mW, the SRS in the fiber increases, and consequently the gain will increase to levels higher than pump power 500 mW as in Fig. 9b. For proposal two, the maximum peak is achieved by the Truewave fiber at distance 30 km and the minimum peak for Freelight fiber at a distance between 80 and 90 km. Finally, at 100 km, the overall gain reaches to 17.27 dB for DSF, 10.33 dB for Freelight and 31.25 dB for Truewave.

In proposal one, the maximum peak for all fibers are close to each other near10 dB at a distance of 20 km and the minimum peak is achieved by DSF below the zero level (i.e. attenuation). Finally, at 100 km, the total gain values are 11.51, 6.9 and 20.83 dB for DSF, Freelight and Truewave fibers, respectively. For the basic model, the minimum peak is archived less than zero at a distance of 70 km by Freelight. The total gain at100 km is 5.76, 3.44 and 10.41 dB for DSF, Freelight and Truewave fibers, respectively.

4.1.3 Raman gain versus fiber length at pump power 700 mW

Figure 9c shows the total gain at pump power 700 mW. The SRS in the fiber increases, leading to an increase in the total gain to levels greater than other pump powers 500 and 600 mW. The total gain in proposal two increases to a peak over 40 dB at 30 km for the Truewave fiber, with its maximum of 46.46 dB at a distance of 100 km. For the other types, gain has a maximum peak at 30 km and reaches to 30.15 dB for DSF and 22 dB for Freelight fibers. For the proposal one, the gain for the three fibers has a peak at 20 km and a minimum peak over zero level at 80 km. However, the maximum gain is at 100 km, where the maximum gain for DSF, Freelight and Truewave fibers is 20, 14.7 and 30 dB, respectively. For the basic model, the minimum peak gain is less than zero between 60 and 70 km, and after that the gain increases due to the backward pump. The maximum gain is obtained at 100 km and is 10 dB for DSF, 7.35 dB for Freelight, and 15.48 dB for Truewave.

4.2 Output signal power with the fiber length at different pump powers

The basic and recommended models' relationship between the output signal power and distance using the three fiber kinds is examined. Figure 10a, b, c illustrates these relations at pump powers of 500,600 and 700 mW and an input power of −4 dBm are used in the basic and the two proposed models.

4.2.1 Output signal power versus fiber length at pump power 500 mW

Figure 10a shows this relation at pump power 500 mW. For the basic model, the output signal power slightly decreases with distance till 40 km. After that, due to the backward pump, it increases slightly up to a distance of 100 km. The power of output signal is −2.6 dBm for DSF, −3.1 dBm for Freelight and −0.57 dBm for Truewave fiber. For proposal two, by the effect of forward pump for the two cascaded RAs, the output signal power sharply increases to its maximum peak between distances of 20 and 30 km for all fibers. Then, it decreases significantly to its minimum peak between distances 80 and 90 km for all fibers. According to the effect of backward pump of the third RA, the

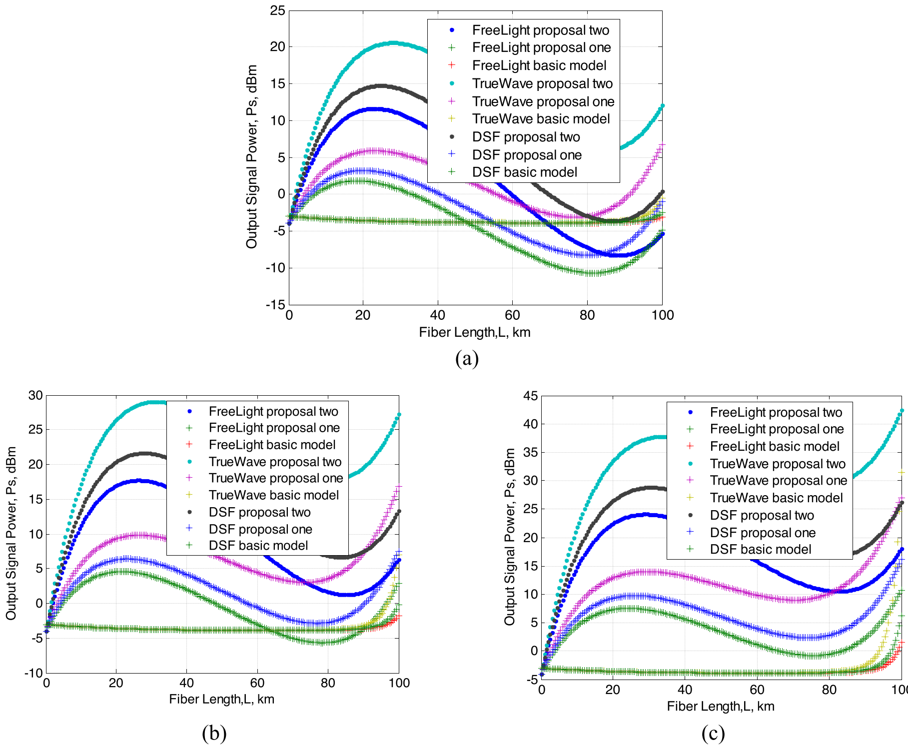

Fig. 10 Output signal power with fiber length for −4 dBm input signal power and pumping power **a** 500, **b** 600 and **c** 700 mW: for basic and the proposed models

output signal power increases again till 100 km, where the output received signal power is 0.4, −5.37 and 12 dBm for DSF, Freelight fiber and Truewave fiber, respectively. For proposal one, and due to the effect of forward pump, the received signal power increases to its maximum peak at 20 km for all fibers. Then, it decreases to its minimum peak at 80 km. Finally, due to the effect of the backward pump in the second RA, the signal power increases till 100 km, where it reaches to −1.06, −4.91 and 6.7 dBm for DSF, Freelight fiber and Truewave fiber, respectively.

4.2.2 Output signal power versus fiber length at pump power 600 mW

Figure 10b shows the results using 600 mW pump power. Increasing pump power increases the SRS which increases the output signal power. In the basic model, the signal power for all fibers are close to each other till a distance of 90 km. After that, the effect of the backward pumping increases the signal power at different levels in each fiber. At 100 km, it reaches to −0.23, −1.78 and 7 dBm for DSF, Freelight fiber and Truewave fiber, respectively.

For proposal two, due to the forward pumping at the cascaded RAs, the signal power increases sharply at high levels in the different fibers to get a maximum peaks at 30 km. Then, it decreases to its minimum peak between distances 80 and 90 km. Finally, it increases by the backward pump power in the third cascaded RA, where at 100 km the

Table 1 Gain for various fiber kinds for the basicand suggested models at various pumping powers: 500, 600 and 700 mW, at amplifier length of 100 km

Fiber Type	Pumping power (mW)	Gain for basic model (dB)	Gain for proposal one (dB)	Gain for proposal two (dB)
DSF	500	1.46	2.93	4.4
	600	5.76	11.51	17.27
	700	10	20	30.15
Freelight	500	0	0	0
	600	3.44	6.9	10.33
	700	7.35	14.7	22
Truewave	500	5.34	10.7	16
	600	10.41	20.83	31.25
	700	15.48	31	46.46

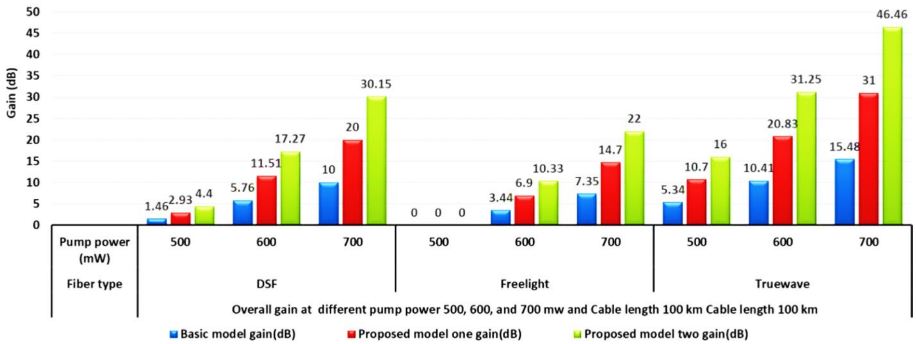

Fig. 11 Gain comparison for the three fibers at 100 km amplifier length at different pumping power

obtained signal power is 13.28 dBm for DSF, 6.34 dBm for Frelight, and 27.26 dBm for Truewave fibers. For proposal one, it increases to levels less than proposal two, where its maximum peaks between 20 and 30 km and minimum at 80 km. The backward pump of the second cascaded RA increases the signal power at 100 km to 7.52, 2.9 and 16.84 dBm for DSF, Freelight and Truewave fibers, respectively.

4.2.3 Output signal power versus fiber length at pump power 700 mW

For 700 mW pump power, the signal power reaches to a level greater than that of pump power 500 and 600 mW as in Fig. 10c. In the basic model, the output signal power slightly decreases with distance in all fibers till 90 km. The backward pump increases the signal power to different levels. At 100 km, the obtained signal power is 6.12 dBm for DSF, 1.44 dBm for Freelight fiber and 31.4 dBm for Truewave fiber. Proposal two shows a sharp increase in the signal power in all fibers. Peaks up are achieved at distance 30 km. Then, it starts decreasing to minimum peaks between 80 and 90 km. At 100 km, the signal power is 26.16,18 and 42.47 dBm for DSF, Freelight and Truewave fibers, respectively. Also, proposal one shows a sharp increase in the signal power for all fibers but less than proposal two. Its Peaks up are achieved between 20 and 30 km. Then, the minimum peaks

Table 2 Comparison of output signal power for basic and proposed models at various pumping powers for various fiber types at 100 km amplifier length

Type of Fiber	Pump power (mW)	Signal power for basic model (dBm)	Signal power for proposal one (dBm)	Signal power for proposal two (dBm)
DSF	500	−2.6	−1.06	0.4
	600	−0.23	7.52	13.28
	700	6.12	16.1	26.16
Freelight	500	−3.1	−4.91	−5.37
	600	−1.78	2.9	6.34
	700	1.44	10.7	18
Truewave	500	−0.57	6.7	12
	600	7	16.84	27.26
	700	31.4	27	42.47

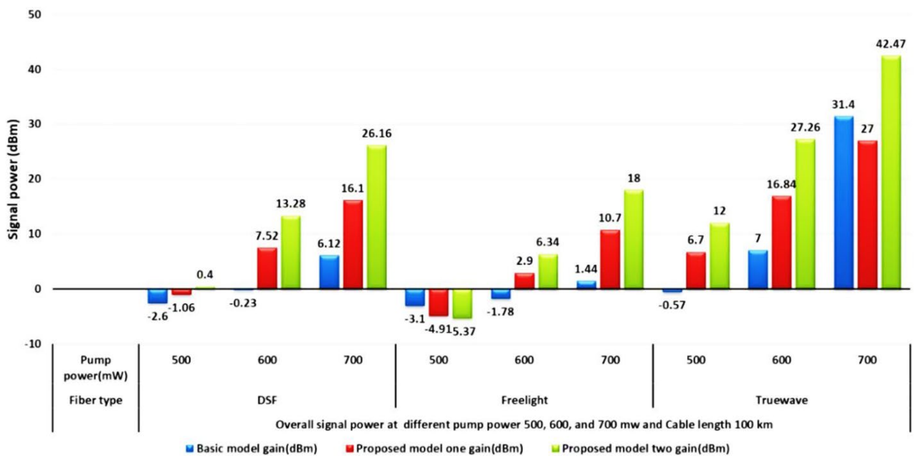

Fig. 12 Output signal power comparison for the three fiber types across 100 km amplifier length at different pumping powers

are achieved between 70 and 80 km. Finally, the signal power at 100 km is obtained as 16.1 dBm for DSF, 10.7 dBm for Frelight and 27 dBm for Truewave fibers.

4.3 Summary of amplifier gain's obtainable Results

The total gain results for the basic and proposed models are summarized at amplifier length of 100 km for the three fiber types, in Table 1, at different pumping powers: 500, 600 and 700 mW.

All obtained gain results are compared in Fig. 11. At pump power 500 mW, the total gain for the proposal two achieves the best results other than proposal one and basic model, where Truewave fiber achieves the best gain of 16 dB at 500 mW pumping power at 100 km.

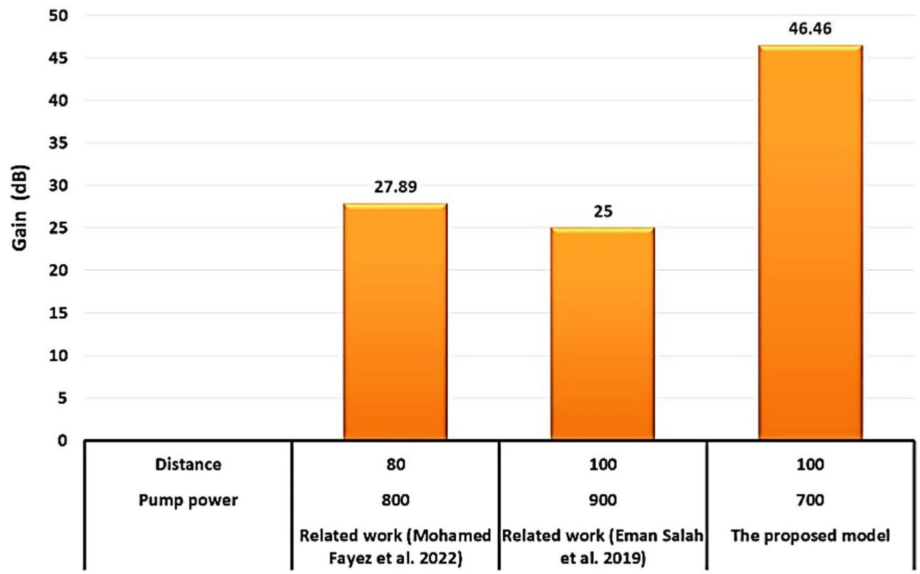

Fig.13 Evaluation of proposal two

Table 3 Comparison between the present results and previous work

References	Best gain obtained (dB)	% Superiority of our model
(Eman Salah et al. 2019)	25	85.84
(Mohamed Fayez et al. 2022)	27.89	66.58
Present work best proposed model (Proposal two)	44.46	–

Also, it is clear that, for the 600 and 700 mW pump powers, proposal two achieves best results especially for Truewave fiber. It gives the best gain 31.25 and 46.46 dB for pump powers 600 and 700 mW, respectively, at the same distance 100 km.

4.4 Summary of the output signal power results

Table 2 summarizes all output signal power for the basic and proposed models using DSF, Freelight fiber, and Truewave fiber at pumping powers of 500,600 and 700 mW.

Figure 12 compares all output signal power results. For all 500 mW pumping power, proposal two shows the best output signal power results 12 dBm in the Truewave fiber. Also, for the pump powers 600 and 700 mW, the best signal power is achieved at proposal two of 27.26 dBm and 42.74 dBm, respectively, for the Truewave fiber.

5 Proposed model assessment

Proposal two of the three cascaded RAs (two cascaded forward pumped and the third is backward pumped) is compared with the related works (Mohamed Fayez et al. 2022, Eman Salah et al. 2019) as in Fig. 13. Obviously, proposal two enhances the overall gain to 46.46 dB at pump level 700 mW using Truewave fiber up to distance 100 km. Compared to the first work (Mohamed Fayez et al. 2022), the overall gain is enhanced (by our work) to 27.89 at pump power 800 mW and a distance of 80 km for the same fiber type. The second related work (Eman Salah et al. 2019) is enhanced by our work to a gain of 25 dB with Truewave fiber for 100 km distance at 900 mW pumping power. So, the proposed model (proposal two) enhances the gain more than 66.58% and 85.84% first and second related works, respectively, pump power than related works. Table 3 summarizes this comparison, showing superiority of our work.

6 Conclusion

Two cascaded RA models are proposed. The first consists of two cascaded RAs; one with a forward pump and the other with a backward pump. The second model consists of three cascaded RAs. RAs one and two have a forward pump and the third has a backward pump. The models are investigated to get the best overall gain and output received signal power at a distance of 100 km with three fibers DSF, Truewave fiber, and Freelight fiber. Three pumping power levels 500, 600 and 700 mW are used. The obtained results are compared between the basic and proposed models. The best overall gain 46.46 dB is obtained at 700 mW pumping power with Truewave fiber. Also, the best output received signal power 42.47 dBm is obtained at the same pump power and fiber type. Finally, results from the suggested models are contrasted with those from earlier publications, where a gain enhancement of 66.58% and 85.84% is achieved.

Author contributions FMM, HAK, AFE, MHA and FAE have directly participated in the planning, execution, and analysis of this study. FMM drafted the manuscript. MHA revised and corrected the manuscript. All authors have read and approved the final version of the manuscript.

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Data availability The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval Not Applicable.

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