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Backward pumped distributed Raman amplifier: enhanced gain

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Abstract

The backward Raman amplifier (RA) can considered as one of the best solutions for optical communication, especially in Wavelength Division Multiplexing technology. They reduce the nonlinear effects, have low noise figure and a wide frequency range. The work in this paper aims to reduce the attenuation of optical signal due to its propagation optical fiber and increase both amplifier gain and output signal power. Two backward Raman models are proposed. Proposal one model consists of two cascaded RAs and the other (proposal two) consists of three cascaded RAs. Three backward pump power levels 200, 400, and 600 mW are used to simulate the models with the three types of fibers: single-mode fiber, Truewave, and Freelight, at an amplifier length of 100 km. Proposal two achieves a maximum gain of 31 dB at 600 mW pump power 600 mW using Truewave optical fiber, with 27.7 dBm maximum output signal power. This proposal is evaluated showing 11.15% gain enhancement and 200 mW saved power when compared to previously published work.

Keywords Raman amplifier (RA) · Backward pumping · Pumping power · Loss · Amplifier gain · Gain parameters

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1 Introduction

Dealing with high data rates especially in data centers and requirements for high bandwidth in 5G/6G networks, the demand is increasing for using advanced transmission networks achieving high data rate and wide bandwidth (Lubana and Kaur 2023). This can be achieved using new approaches for modulation format and high data rate transmission network equipment (Akasaka et al. 2023; Wang et al. 2021). A new transmission technique has been introduced to increase information capacity is the wavelength division multiplexing (WDM) (Anurupa and Malhotra 2019). In WDM systems, all information are modulated into the form of wavelengths (channels) which are multiplexed together at transmitter and then transmitted through the optical fiber. At the receiver, the wavelengths are demultiplexed individually and then converted to information once again (Ahuja and Meena 2019; Mustafa et al. 2022). A WDM technology practically gives attractive properties as reducing number of fibers, low attenuation, small signal power, higher bandwidth, reduced signal distortion, and small space equipment. Irrespective of all previous WDM properties, many unwanted factors in the optical fiber reduce WDM performance as attenuation, dispersion, and nonlinear effects (Sayed et al. 2021).

Attenuation reduces the optical signal power gradually with propagation inside optical fiber, which cannot travel to long distances. So, it needs to compensate its optical power at certain distances. Optical amplifiers can compensate the optical power according to its gain. Optical amplifiers have the ability to amplify the optical signal in the optical form without optical-electrical-optical conversions. Amplifiers are used in many optical transmission technologies as Dense WDM (DWDM) and Space Division Multiplexing (SDM) to compensate the optical power during propagation in optical fiber for travelling to long-haul distances with high data rate transmission (Kilinçarslan et al. 2023). Although optical amplifiers are very beneficial, they generate noise and increase nonlinear phenomena resulting in some harmful effects on the network that reduce the network performance.

Different techniques are used to amplify the optical signal power through many types of amplifiers as Semiconductor Optical Amplifier (SOA), Erbium Doped Fiber Amplifier (EDFA), and RA (Dhar et al. 2021, Mahran 2016a, Mahran 2016b, Mahran 2016c, Lubana and Kaur 2021, Lubana et al. 2020). RAs can be considered one of the most common amplifiers used in the optical fiber applications. They utilize high data rate operation and increase the system performance, where the signal can propagate to a maximum reach. The main issue of amplification in RA is the Stimulated Raman Scattering (SRS) in the silica molecules in optical fiber due to the power pump. As the pump power increases, the total gain also increases. So, the total gain can be adjusted to a certain value as required by the network design (Borraccini et al. 2022).

RAs can be classified into two types: distributed and discrete amplifiers. The discrete RA is used to amplify the WDM optical wavelengths at the short S-band at windows 1300 nm and 1550 nm. The distributed Raman amplifier (DRA) introduces enhanced noise figure and reduces the nonlinear effects in the optical fiber span. So, it can improve some properties of optical fiber span as longer propagation distance, higher data rate, and operating near the zero dispersion wavelengths (Islam et al. 2007, Eadley and Agrawal 2005). The DRA gives the optical fiber network attractive benefits than discrete especially in WDM network as (1) low power channel can be used, (2) it can compensate signal power for high loss repeaters, (3) it can divide very long distance span to multi-uniform gain along the fiber lengths, and (4) it enhances the signal to noise ratio (SNR) beside a decreased nonlinear penalty (Beshr and Aly 2020).

Amplified spontaneous emission (ASE) noise is lower in the DRAs than other type as EDFAs which gives it attractive benefits than EDFA (Zhang et al. 2022). Multiple Raman pumps in DRA give it a much wider gain profile which increases its bandwidth and its capacity.

Another approach which can perform Raman amplification is using cascaded Raman technique. A cascaded Raman technique is using more than one Raman stage which can give wider bandwidth, flatness, and higher gain (Al-Alimi et al. 2017). The cascaded Raman technique gives more useful proprieties; however, the needs for high pump power is urgent. Many researches are carried out by using one Raman and multi-stage RAs at different pump power levels and the three types of fibers: single-mode fiber (SMF), Truewave, and Freelight are considered. In (Saber et al. 2019), two stages RAs in a cascaded form are presented to enhance the amplifier gain. Two types of pumping schemes are used; one is forward pump in the first stage and the other is backward pump up to distance 100 km under different pump power levels and different fiber types. Most parameters affecting on Raman gain are simulated and compared. In (Salah et al. 2019), one RA gain and output signal power are investigated at different pump powers and different fiber types for distance 100 km. In (Fathy et al. 2019), RA is used with a backward pump, where the gain affecting parameters are simulated and observed at different pump powers and fiber types. Finally in (Fayez et al. 2022), two RAs backward pumped are cascaded and presented to overcome gain attenuation at a distance of 80 km; the first and second RAs have different backward pump levels using three fiber types. The overall gain and signal power were simulated at the same parameters.

In this work, three cascaded RAs are proposed to overcome gain attenuation and improve signal power for 100 km distance using three fiber types SMF, Freelight, and Truewave at different backward pump powers. A comparison is performed between one RA (basic model), two cascaded RAs (proposal one), and three cascaded RAs (proposal two) are discussed and evaluated using Matlab simulation with the related work. The remainder of this paper is structured as follows. Section 2 illustrates the basic model and analysis. The proposed model is described in Sect. 3. Section 4 displays and discusses the simulation results. The proposed model is evaluated in Sect. 5. Section 6 is devoted to the main conclusions.

2 Basic model and analysis

This section shows the components, concepts and operation equations for a distributed backward pumped RA. The block diagram is illustrated in Fig. 1.

The amplifier components in details are shown in Fig. 2. The system consists of (1) an optical fiber, (2) an optical pump power, and (3) a coupler. The optical pump power is coupled into the optical fiber opposite to the input optical signal. SRS is induced into the optical fiber by the pump power. The power of the pump is transferred to the optical weak signal power which is amplified during its propagation through effective section at the fiber end. The amplified signal gets out through the coupler to the receiver (Toeima and Aly 2009, Rashed 2011, Felinsky et al. 2008, Salah et al. 2019).

The differential equations which describe not only signal and pump power attenuation according to propagation but also the transferring pump power to signal power are (Fathy et al. 2019, Mohamed et al. 2019, Jordanova et al. 2008):

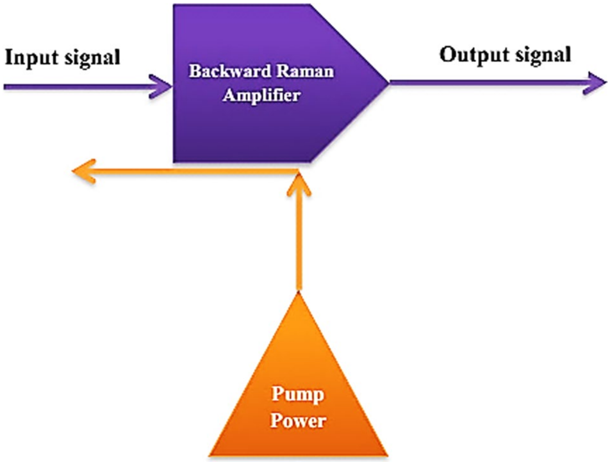

Fig. 1 Block diagram of a backward pumped RA

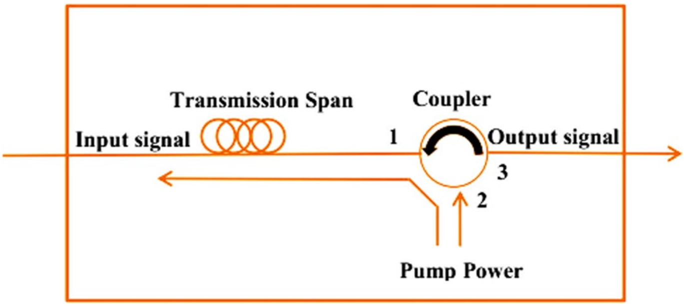

Fig. 2 Backward pumped RA system (Al-Alimi et al. 2017)

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

$$G_R P_r P_i - \alpha_i P_i \tag{2}$$

where G_R refers to gain coefficient (W^{-1} m^{-1}). The attenuation coefficients α_i and α_r are related to the optical power for the signal and the pump, respectively. The angular frequencies of the optical signal and the pumping power are ω_i and ω_r, respectively (Jyoti Dhir et al. 2014).

The pump power at point z, P_r, can be calculated by:

$$\mathrm{P_r(Z) = SP_r(0) \cdot e^{-\alpha_r Z(1-s)} = P_r(0) \cdot e^{-\alpha_r (L-Z)}} \tag{3}$$

If the pump power is substituted and ranged from 0 to L in Eq. (2), the signal power at the forward and back pump can be give by (Singh 2014, Makoui et al. 2009, Mashade and Abdel Aleem 2009, Saber et al. 2019):

$$\mathrm{P}_i(\mathrm{Z}) = \mathrm{P_i(0) \cdot e^{\left(G_R P_0\left(\frac{(1-\exp(-\alpha_r Z))}{\alpha_r}\right)-\alpha_i Z\right)} = G_F \cdot P_s(0)} \tag{4}$$

$$P_i(Z) = P_i(0) \cdot e^{\left(G_R P_0 \left(\frac{\exp(-\alpha_r L)(1-\exp(-\alpha_r Z))}{\alpha_r}\right) - \alpha_i Z\right)} = G_B \cdot P_{is}(0) \tag{5}$$

where the gains G_F and G_B correspond to forward and backward pumped amplifier, respectively, P(0) is the pump power at the end of the input, the linear signal and pump energy attenuation coefficients α_i and α_r in the optical fibers are expressed as:

$$\alpha_{i,r} = {}^{\alpha}/_{4.343} \tag{6}$$

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

3 Proposed model

The proposed model consists of two schemes. The first one (proposal one) is two cascaded backward pumped RAs. The second one (proposal two) is three cascaded backward pumped RAs. Each scheme is modeled with its connections and mathematical equations which describe the relation between different parameters in backward pumped RAs.

3.1 Proposal one (Two cascaded RAs)

This scheme is illustrated in the block diagram shown in Fig. 3.

Figure 4 illustrates the connection in details for the model. The first backward pumped amplifier output is connected to the input of the second amplifier, where the combination output is from the second RA to enhance the overall gain.

The total gain of the two cascaded RAs could be produced from Eqs. (4) and (5) by utilizing two RAs pumped in a cascaded form to boost the Raman gain which can be expressed as:

$$G_T = \frac{G_B}{i(G_B)} \tag{7}$$

where G_T is the overall gain of backward pumped RA and i denotes the number of units from backward pumped RA.

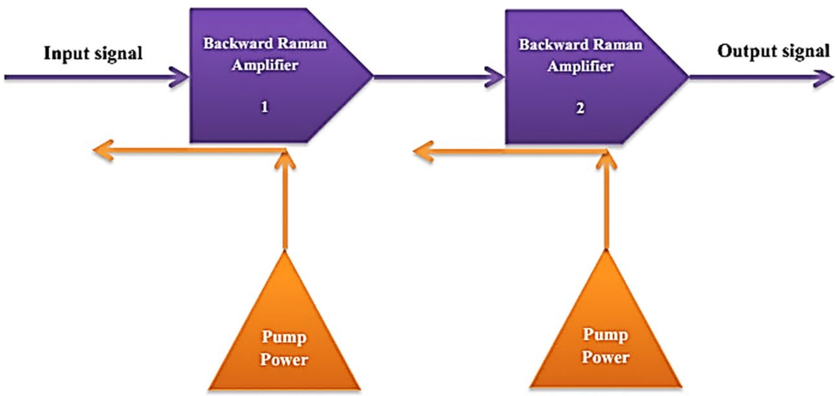

Fig. 3 Block diagram of proposal one (two RAs in a cascaded form)

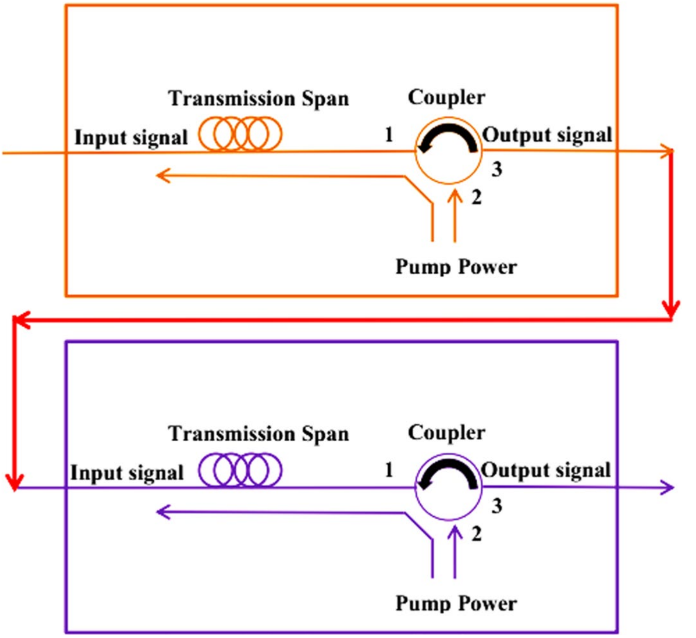

Fig. 4 Design model of two cascaded RAs (Fayez et al. 2022)

Then

$$G_T = exp\left[g_R P_0 \times \frac{\exp(-\alpha_P L_1)(\exp(\alpha_P z) - 1)}{\alpha_P} - \alpha_S Z\right] / exp\left[g_R P_0 \times \frac{1 - \exp(-\alpha_P L_2)}{\alpha_P} - \alpha_S Z\right] \tag{8}$$

$$G_T = exp\left[g_R P_0 \times \frac{\exp(-\alpha_P L_1)(\exp(\alpha_P z) - 1)}{\alpha_P} - i\left(g_R P_0 \times \frac{\exp(-\alpha_P L_2)(\exp(\alpha_P z) - 1)}{\alpha_P}\right)\right] \tag{9}$$

$$G_T = exp\left[g_R P_0 x \frac{(\exp(-\alpha_P l_1) - \exp(-\alpha_P l_2))(\exp(\alpha_P z) - 1)}{\alpha_P}\right] \tag{10}$$

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

$$P_i(L) = P_i(0) \exp\left(\frac{g_0 P_0 L}{A_{eff}} - \alpha_i L\right) \tag{11}$$

The length at which the SRS, or the nonlinear effect, still manifests itself in optical fibers is known as the effective length, L_{eff}, and is defined as (Fayez et al. 2022):

$$L_{eff} = \frac{1 - \exp(-\alpha_r L)}{\alpha_r} \tag{12}$$

The power signal ratio with or without Raman amplification is the definition of the amplifier gain and is therefore obtained by:

$$G_A = \frac{P_i}{P_i(0)\exp\left(-\alpha_i L\right)} \tag{13}$$

3.2 Proposal two (Three cascaded RAs)

In this scheme, three RAs are connected in cascaded, where each RA has its own pump power as illustrated in Fig. 5.

The output power of the first RA is connected to the input power to the second one. The output power of the second RA is connected to the third one as shown in details in Fig. 6. The overall output gain is obtained from the third RA.

The overall gain, G, of the three cascaded RAs could be obtained from Eqs. (4) and (5) as:

$$G = \frac{G_1}{G_2 \times G_3} \tag{14}$$

$$G = \frac{exp\left[g_R P_0 x \frac{\exp\left(-\alpha_P l_1\right)(\exp\left(\alpha_P z\right)-1}{\alpha_P} - \alpha_S Z\right]}{exp\left[g_R P_0 x \frac{\exp\left(-\alpha_P l_2\right)(\exp\left(\alpha_P z\right)-1}{\alpha_P} - \alpha_S Z\right] \times exp\left[g_R P_0 x \frac{\exp\left(-\alpha_P l_3\right)(\exp\left(\alpha_P z\right)-1}{\alpha_P} - \alpha_S Z\right]} \tag{15}$$

$$G = exp\left[g_R P_0 x \frac{(\exp\left(-\alpha_P l_1\right) - \exp\left(-\alpha_P l_2\right) - \exp(-\alpha_P l_3))\left(\exp\left(\alpha_P z\right) - 1\right)}{\alpha_P} + \alpha_S Z\right] \tag{16}$$

where G_T is the overall gain of three cascaded backward pumped amplifiers, and $L_{1,}$ L_2 and L_3 are their fiber lengths.

4 Results and discussion

The relation between the proposed models gain, basic model and signal power with the distance up to 100 km is displayed and discussed using Matlab simulation at three backward pump power levels (200, 400, and 600 mW) using the three types of fibers: single-mode fiber (SMF), Truewave, and Freelight.

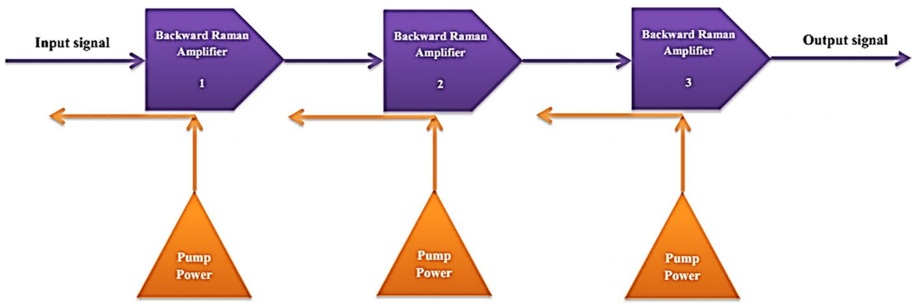

Fig. 5 Block diagram of proposal two (three RAs in a cascaded form)

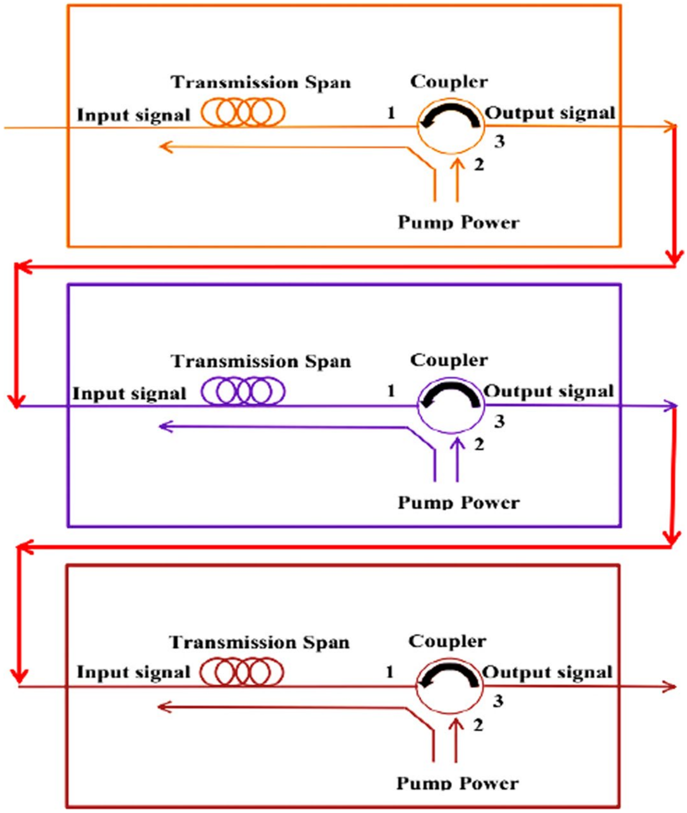

Fig. 6 Design model of three cascaded amplifiers

4.1 Raman gain versus fiber length for different fiber types at different pumping powers

The relationship between gain and fiber length for each of the three types of fiber (SMF, Freelight and Truewave) is investigated as follows. The comparison between using different fiber type for the relation between the gain and distance at backward pump power 200 mW is illustrated in Fig. 7. For the basic model, the gain is decreased as the distance increased. At 60 km, the effect of the backward pump does not enhance the gain, where it still a loss at 100 km for the three fiber types. The gain for the two and three cascaded RAs increases slightly over zero. After 60 km, the gain increases as the distance increases by the backward pump effect for the three fiber types. At 100 km, for two cascaded RAs the gain is enhanced to 2.6, 3.3, and 4.3 dB for SMF, Freelight, and Truewave, respectively. The gain for the three cascaded RAs is enhanced to 6.3, 8, and 10.32 for SMF, Freelight, and Truewave fiber type, respectively.

The same discussion applies at 400 mW and 600 mW pump power. For 400 mW, at 100 km, the two cascaded RAs give gain 5.2, 6.7, and 8.6 dB for SMF, Freelight, and Truewave fiber type, respectively. The three cascaded RAs give gain 12.5, 16.15, and 20.64 dB for SMF, Freelight, and Truewave fiber type, respectively. While, for 600 mW, at 100 km, the two cascaded RAs enhance the gain to 7.8, 10, and 13 dB for SMF, Freelight, and

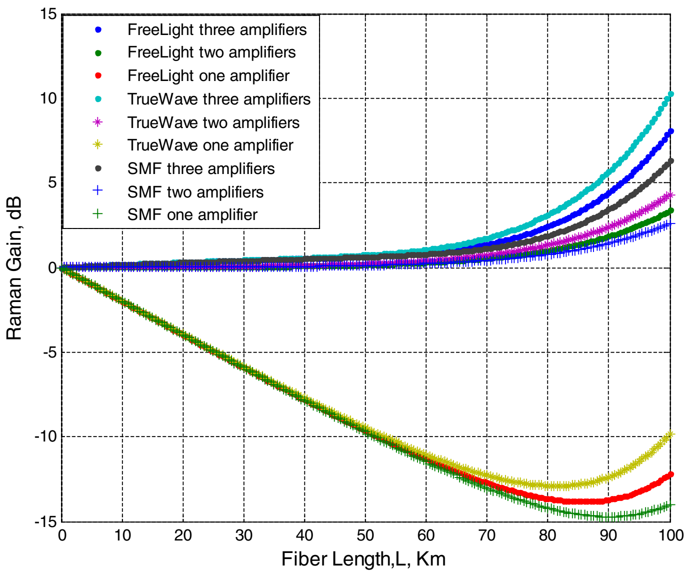

Fig. 7 Raman gain versus fiber length for different types of fiber at 200 mW pumping power: basic model and proposed models

Truewave fiber type, respectively. Here, the three cascaded RAs enhance the gain to 18.8, 24.23, and 31 dB for SMF, Freelight, and Truewave fiber type, respectively. This is clarified, respectively, in Figs. 8 and 9.

4.2 Output power signal characteristics for backward pumping at different pumping powers

This section investigates the relation between the signal power and the distance for the basic and both proposed models at −3 dBm input power for the three fiber types: SMF, Freelight and Truewave at different pump powers of 200, 400, and 600 mW.

Figure 10 shows the relation between the overall output signal power and the distance at 200 mW pump power for the three fiber types. For the basic model, the received (output) power decreases as the distance increases. After 60 km, it starts to increase due to the effect of the backward pumping and according to fiber type until 100 km. The overall output signal power is − 17, − 15.2, and − 12.85 dBm for SMF, Freelight and Truewave, respectively. Here, the obtained signal power is very low and acts as loss compared to input power − 3 dBm.

For both proposed models, the signal power increases slightly as the distance is increased. At 60 km, with the effect of backward pump, it starts to increase, where a large amount of pump energy is transferred to signal according to different fiber type, and the received (output) power is gained. For the two cascaded RAs at 100 km, the signal power is − 0.38, 0.37, and 1.31 dBm for SMF, Freelight and Truewave respectively. Also, for three cascaded, at 100 km, it has the values of 3.31, 5.07, and 7.25 dBm for SMF, Freelight and Truewave, respectively.

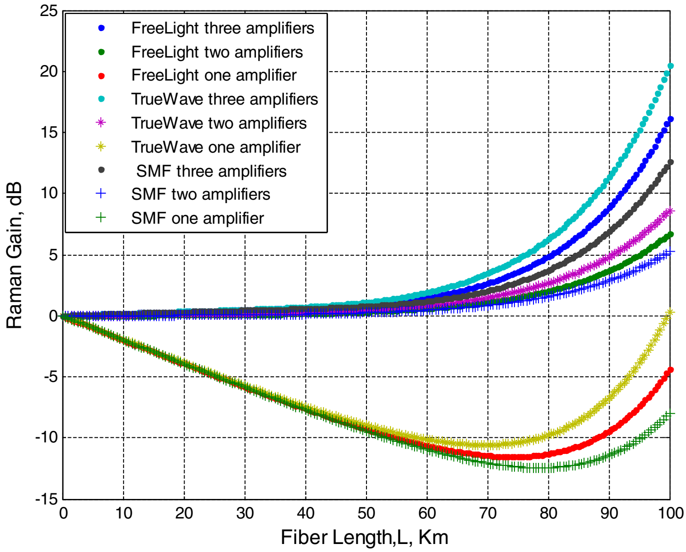

Fig. 8 Raman gain versus fiber length for different types of fibers at 400 mW pumping power: basic model and proposed models

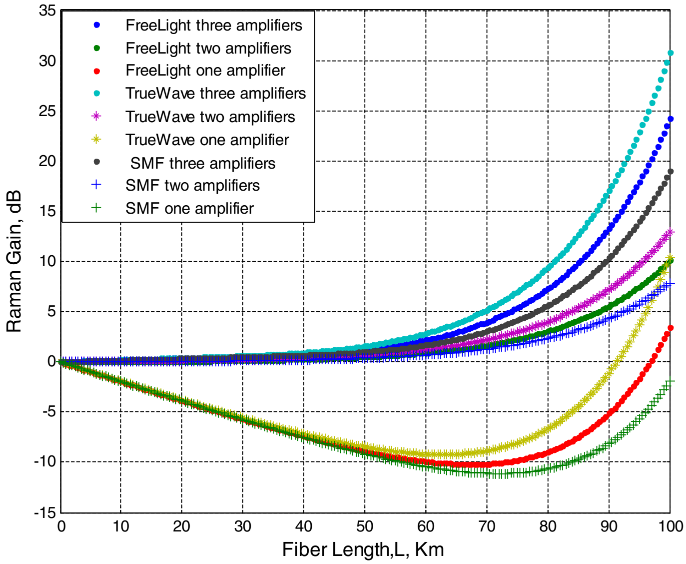

Fig. 9 Raman gain versus fiber length for different types of fiber at 600 mW pumping power: basic model and proposed models

Repeating for 400 mW pump power, at 100 km, the output signal power is − 11 dBm for SMF and − 7.36 dBm for Freelight which are not subjected to gain. However, − 2.7 dBm for Truewave can be gained adequately by backward pump. All proposed models increases the signal power by a small amount as distance increases. After 60 km, it starts to increase

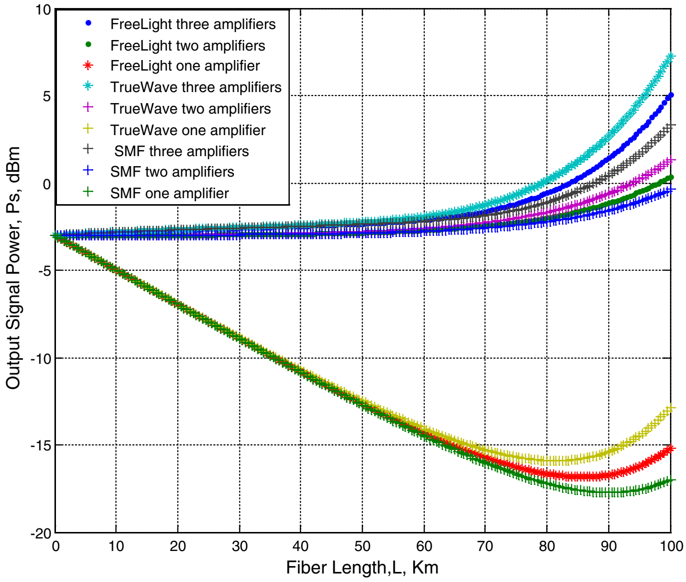

Fig. 10 Output signal power versus fiber length at 200 mW pumping power and −3 dBm input signal power: basic model and the proposed models

according to effect of backward pump. At 100 km, the two cascaded RAs achieves an output signal power of 2.23, 3.7, and 5.6 dBm for SMF, Freelight and Truewave, respectively. The corresponding output signal power for the second proposal is 9.63, 13.15, and 17 dBm for SMF, Freelight and Truewave, respectively. This is illustrated in Fig. 11.

Figure 12 depicts the output signal power at 600 mW. At 100 km, the two cascaded RAs (proposal one) gives 4.85, 7.1, and 10 dBm for SMF, Freelight and Truewave, respectively, while the second proposal (three cascaded RAs) achieves more attractive received (output) power of 16, 21.23, and 27.7 dBm, for the three fiber types, respectively.

5 Summary of obtained results of amplifier gain

In the following, we summarized the obtained results in the form of comprehensive comparisons. Table 1 compares the RA gain at a distance of 100 km at different pump powers (200, 400, and 600 mW) for the three fiber types; SMF, Freelight, and Truewave, for the basic model and the two proposed schemes.

Figure 13 also summarizes the obtained results in another form.

It is clear that, for the SMF fiber, the best overall gain (18 dB) is achieved by proposal two (three cascaded RAs) at 100 km, with 600 mW backward pump power. Also for Freelight, the three cascaded RAs (proposal two) gives 24.23 dB with 600 mW pump power 600 mW, while the best overall gain is 31 dB for the Truewave fiber at the same pump power.

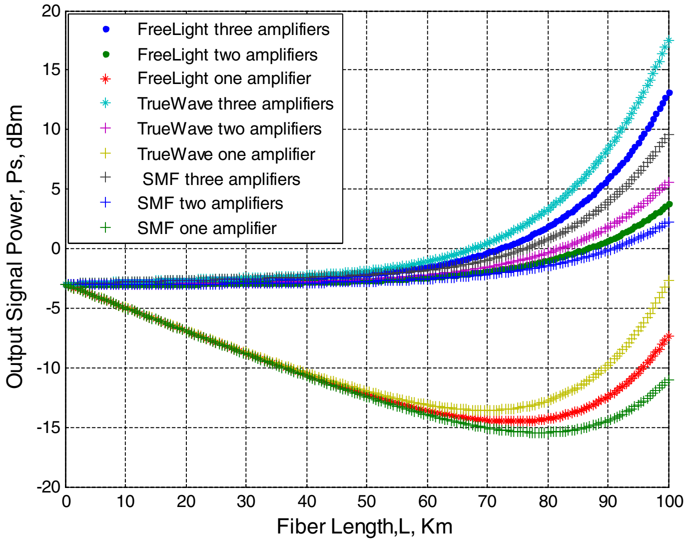

Fig. 11 Output signal power versus fiber length at 400 mW pumping power and −3 dBm input signal power: basic model and the proposed models

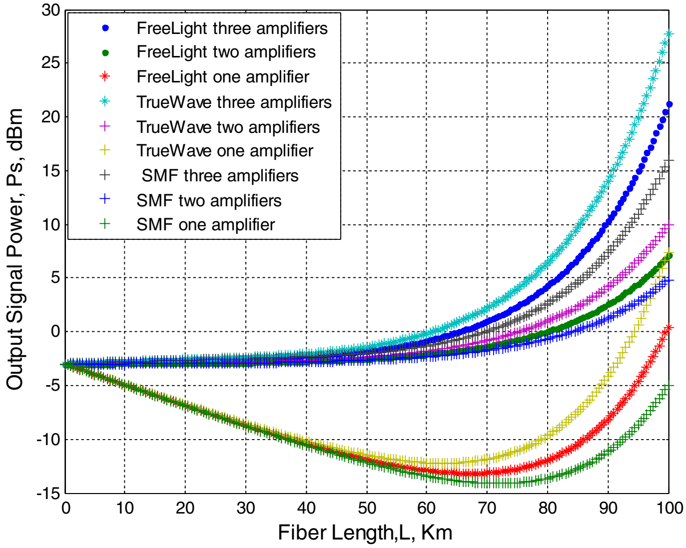

Fig. 12 Output signal power versus fiber length at 600 mW pumping power and −3 dBm input signal power: basic model and the proposed models

Table 1 Gain comparison between different fiber types for basic model and proposed models at different pumping powers: 200, 400 and 600 mW, at 100 km amplifier length

Fiber type	Pump power (mW)	Gain (g_{max}) for one backward pumped RA (Basic model) (dB)	Gain (g_{max}) for two backward pumped RAs (Proposal one) (dB)	Gain (g_{max}) for three backward pumped RAs (Proposal two) (dB)
SMF	200	0	2.6	6.3
	400	0	5.2	12.5
	600	0	7.8	18.8
Freelight	200	0	3.3	8
	400	0	6.7	16.15
	600	3.44	10	24.23
Truewave	200	0	4.3	10.32
	400	0	8.6	20.64
	600	10	13	31

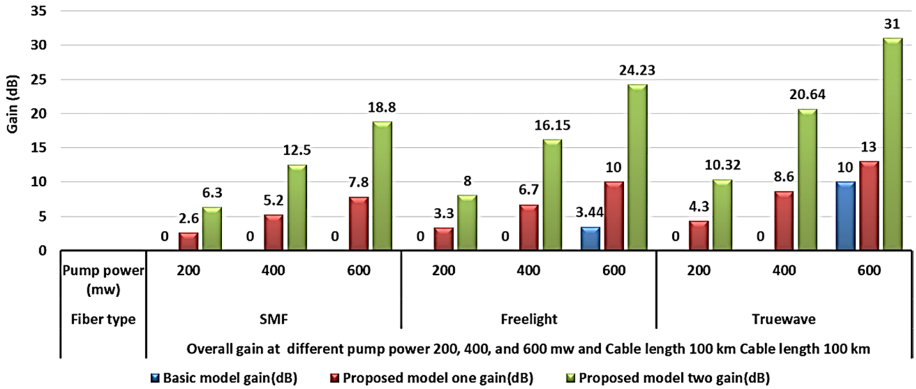

Fig. 13 Gain comparison results for the three fiber types at an amplifier length of 100 km at 200, 400, and 600 mW pump power

6 Summary of obtained results of output signal power

Table 2 summarizes and compares the received power (output signal power), for all fiber types, at 100 km amplifier length and different pump powers: 200, 400, and 600 mW.

The amplifier output power is also compared in Fig. 14, at 100 km and different pump powers for all fiber types. As shown, the SMF gives the best signal power of 16 dBm using proposal two (three cascaded amplifiers) at 600 mW pump power 600 mW. At the same distance and pump power, the same proposal achieves 21.23 dBm and 27.7 dBm, for the Freelight and Truewave fibers, respectively.

7 Proposed model evaluation

Since, in general, proposal #two gives better results than proposal #one, so, more care will be devoted to this proposal. The second proposal model of three cascaded RAs is evaluated through a comparison with the work of Fayez et al. (2022) as illustrated in Fig. 15. Here, the maximum gain using the Truewave fiber type at a distance of 100 km and a pumping power of 600 mW enhances the gain to 31 dB, where the related work gain is only 27.89 dB at 80 km and 800 mW pumping power. This enhancement assures the superiority of our proposal, where the gain achieves 11.15% increase and saves 200 mW pumping power.

8 Conclusion

In this paper, two models are proposed to enhance the RA gain, consisting of two and three cascaded RAs, respectively. Three backward pump power levels of 200, 400, and 600 mW are used with three fiber types: SMF, Freelight, and Truewave at an amplifier length of 100 km. The relation between gain and distance up to 100 km are displayed and discussed using Matlab simulation for the three fiber types for the basic model and the proposed models. In general, proposal two gives better results than proposal one. It is found the Truewave fiber gives 31 dB, which is the best maximum gain at 600 mW backward pump power by

Table 2 Received power comparison between different fiber types for basic model and proposed models at different pumping powers: 200, 400 and 600 mW, at 100 km amplifier length

Type of fiber	Pump power (mW)	Signal power for one backward pumped RA (Basic Model) (dBm)	Signal power for two backward pumped RAs (Proposal One) (dBm)	Signal power for three backward pumped RAs (Proposal Two) (dBm)
SMF	200	−17	−0.38	3.31
	400	−11	2.23	9.63
	600	−4.9	4.85	16
Freelight	200	−15.2	0.37	5.07
	400	−7.36	3.7	13.15
	600	0.44	7.1	21.23
Truewave	200	−12.85	1.31	7.25
	400	−2.7	5.6	17.5
	600	7.42	10	27.7

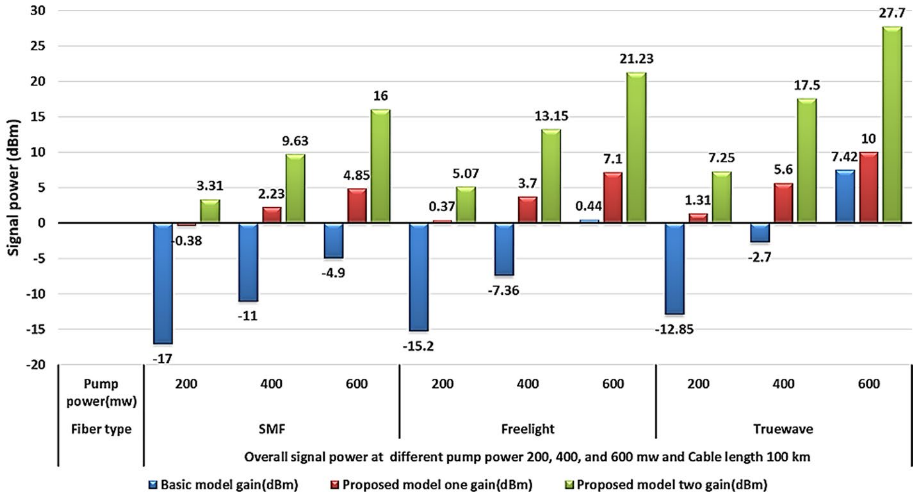

Fig. 14 Amplifier output power comparison results for the three fiber types at 100 km amplifier and 200, 400, and 600 mW pump power

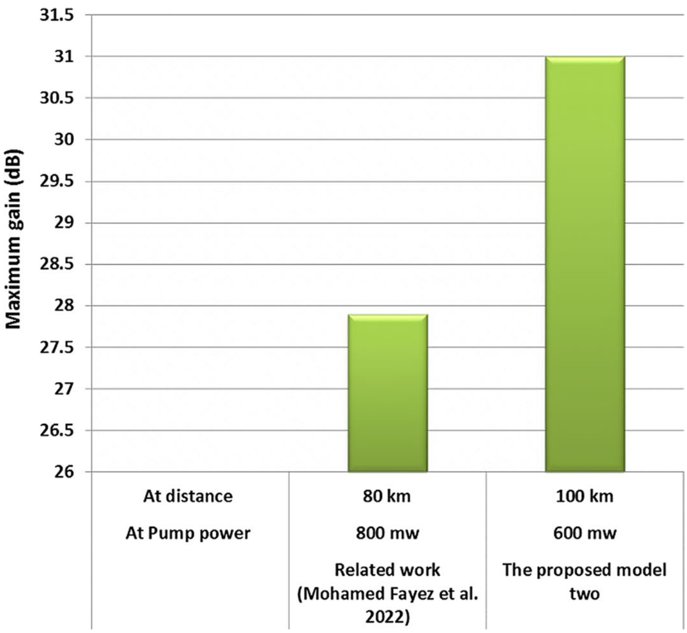

Fig.15 Evaluation of proposal #two

proposal two. Also, the output signal power is simulated and discussed with the distance up to 100 km, where a maximum signal power of 27.7 dBm is achieved by the Truewave fiber with the same proposed model. Finally, proposal two is evaluated and compared by a previously related work, showing 11.15% gain improvement and 200 mW saved power.

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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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