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Full Length Research Paper

High performance efficiency of distributed optical fiber Raman amplifiers for different pumping configurations in different fiber cable schemes

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Fiber Raman amplifiers (FRAs) are attractive for ultra wide dense wavelength division multiplexing (UW-DWDM) transmission systems due to their advantages of broad amplification bandwidth and flexible central wavelength. With recent developments of optical pump sources with high power near 1.4 μm wavelength and highly nonlinear fiber having a peak effective Raman gain coefficient, more than ten times that of conventional single mode fiber, distributed FRAs (DFRAs) are emerging as a practical optical amplifier technology, especially for opening new wavelength windows such as the short and ultra long wavelength bands. Optical pump powers required for Raman amplification were significantly higher than that for erbium-doped fiber amplifier (EDFA), and the pump laser technology could not reliably deliver the required powers. However, with the improvement of pump laser technology, Raman amplification is now an important means of expanding span transmission reach and capacity. In the present paper, we have deeply investigated the proposed model for optical DFRAs in the transmission signal power and pump power within Raman amplification technique in co-pumped, counter-pumped and bi-directional pumping direction configurations through different types of fiber cable media. The validity of this model was confirmed by using experimental data and numerical simulations.

Key words: Distributed fiber Raman amplifier, signal power, pumping power, forward pumping, different fiber media, backward pumping, bidirectional pumping configuration.

INTRODUCTION

The first fiber optical telecommunication systems emerged with the engineering of low loss optical fiber (Maan et al., 2009). Even though the complexity of the system has increased, the basic elements remain the same. They consist of an optical source, a means of modulating the source, the transmission medium (that is, the optical fiber), and a detector at the output end of the fiber. Fiber loss is one limitation to the transmission distance of this system. In the early days of fiber-optic communications, the loss of the fiber was compensated for in long spans by using electrical regenerators. As their name implies, these devices detected the signal, converted it to an electrical signal, and using a new laser transmitted a new version of the signal. Electrical regenerators were expensive and also limited the rate at which data could be transmitted as time for the much slower electrical processing to occur had to be built into the system. In order to overcome the limitations imposed by electrical regeneration, a means of optical amplification was sought. Two competing technologies emerged: the first was erbium-doped fiber amplifiers (EDFA) (Raghavendra and Vara, 2010; Abd El-Naser and Ahmed, 2010) and the second Raman amplification (Ming-Jun and Daniel, 2008). In the first deployed systems, EDFA emerged as the preferred approach. One reason was that the optical pump powers required for

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Raman amplification were significantly higher than that for EDFA, and the pump laser technology could not reliably deliver the required powers. However, with the improvement of pump laser technology, Raman amplification is now an important means of expanding span transmission reach and capacity (Abd El-Naser et al., 2009).

In a multiple wavelength telecom system, it is important that all signal wavelengths have similar optical powers. The variation in the gain provided to different wavelengths after passing through an amplifier is referred to as the gain flatness. If the signal at one wavelength is disproportionately amplified, as it passes through several amplifiers, it will grow super linearly relative to the other channels reducing the gain to other channels (ITU-T Recommendation G.652, 2009). The system, however, will still be limited by the channel with the lowest gain. As a result, after each amplifier the gain spectrum generally is flattened. One approach is to insert wavelength-dependent lossy elements, within the amplifier, with the appropriate spectral profile. Raman amplification offers the ability to achieve this without lossy elements. In Raman amplification, a flat spectral profile can be obtained by using multiple pump wavelengths (Abd El-Naser et al., 2009; Shahi et al., 2009). For a given fiber, the location of the Raman gain is only dependent on the wavelength of the pump, the magnitude of the gain is proportional to the pump power, and the shape of the gain curve is independent of the pump wavelength. Therefore, if multiple pumps are used a flat spectral gain profile can be obtained (Banerjee, 2009). The required pump wavelengths and the gain required at each wavelength can be predicted by summing the logarithmic gain profiles at the individual pump wavelengths (Abd El-Naser and Ahmed, 2009).

In the present study, we have deeply analyzed the signal power, pumping power, rate of change of signal, pumping powers with respect to transmission distance under the variations of signal, pump powers and signal and pump wavelengths for different fiber link media in different pumping direction configurations (forward, backward, and bidirectional) over wide range of the operating parameters.

DEVICE MODELING ANALYSIS

Signals fad with distance when they traveling through any type of media. As the optical signal moves along a SMF, it gets attenuated along the fiber. The signal power when it travels through the distance z without any amplification, P_{sWNA} can be expressed as follows:

$$P_{sWNA}(z) = P_{so}\exp(-\alpha_{Ls}z) \quad (1)$$

Systems avoid this problem by amplifying signals along the way. So there is a need for using optical fiber amplifiers. The evolution of the input signal power (P_s) and the input pump power (P_p) propagating along the single mode optical fiber in watt, can be quantitatively described by different equations called propagation equations. The rate of change of signal and pump power with the distance z, can be expressed as mentioned in Makoui et al. (2009):

$$\frac{dP_p}{dz} = -\alpha_{Lp}P_p(z) - \frac{\lambda_s}{\lambda_p}g_{\mathrm{Reff}}P_s(z)P_p(z) \quad (2)$$

$$\frac{dP_s}{dz} = -\alpha_{Ls}P_s(z) + \frac{\lambda_s}{\lambda_p}g_{\mathrm{Reff}}P_s(z)P_p(z) \quad (3)$$

Where λ_s and λ_p are the signal and pump wavelengths in µm, respectively, z is the distance in km from z=0 to z=L, α_{Ls} and α_{Lp} are the linear attenuation coefficient of the signal and pump power in the optical fiber in km^{-1}, respectively, The linear attenuation, α_L can be expressed as follows:

$$\alpha_L = \alpha/4.343 \quad (4)$$

Where α is the attenuation coefficient in dB/km. g_{Reff} is the Raman gain efficiency in $W^{-1}km^{-1}$ of the fiber cable length, L in km, which is a critical design issue and is given by the equation as follows:

$$g_{\mathrm{Reff}} = \frac{g_R}{A_{eff} \times 10^{-18}} \quad (5)$$

Where g_R is the maximum Raman gain in km W^{-1}, A_{eff} is the effective area of the fiber cable used in the amplification in μm^2. Equation 1 can be solved when both sides of the equation are integrated. When using forward pumping, the pump power can be expressed as follows (El Mashade, et al., 2009):

$$P_{PF}(z) = P_{poF}\exp(-\alpha_{Lp}z) \quad (6)$$

Where P_{PoF} , is the input pump power in the forward direction in watt at z=0.

In the backward pumping, the pump power is given by Abd El Naser et al. (2009):

$$P_{PB}(z) = P_{poB}\exp[-\alpha_{Lp}(L-z)] \quad (7)$$

Where P_{PoB} , is the input pump power in the backward direction in watt at z=L.

In the case of bidirectional pump, both of the pump can be equal or different in the used wavelength or the used amount of power, therefore, in this case, the following equation can be used to calculate the pump power at point z (Raghuawansh et al., 2006):

Table 1. Typical values of operating parameters in proposed model.

Operating parameter	Symbol	Value			
Operating signal wavelength	λ_s	$1.45 \le \lambda_s$, μm ≤ 1.65			
Operating pump wavelength	λ_p	$1.40 \le \lambda_p$, μm ≤ 1.44			
Input signal power	P_{so}	$0.002 \le P_{so}$, W ≤ 0.02			
Input pump power	P_{po}	$0.165 \le P_{po}$, W ≤ 0.365			
Percentage of power launched in forward direction	r_f	0.5			
Attenuation of the signal power in silica-doped fiber	α_S	0.25 dB/km			
Attenuation of the pump power in silica-doped fiber	α_P	0.3 dB/km			
Types of fiber cable media		True wave reach fiber	LEAF (NZ-DSF)	SMF-28 (NDSF)	Unit
Effective area	A_{eff}	55	72	84.95	$(\mu m)^2$
Raman gain efficiency	g_{Reff}	0.6	0.45	0.38	$(W.km)^{-1}$

$$P_{PFB}(z) = (rf)P_{poF}\exp(-\alpha_{Lp}\, z) + (1-rf)P_{poB}\exp[-\alpha_{Lp}(L-z)] \qquad (8)$$

Where r_f is the percentage of pump power launched in the forward direction. If the values of P_P are substituted in differential Equation 2, and is integrated from z=0 to z=L for the signal power in the forward and the backward pumping, the result mathematical equation can be written as mentioned in Abd El Naser et al. (2009):

$$P_S(z) = P_{so}\exp\left[\left(\frac{g_R}{A_{eff}}\right)P_{po}\, L_{eff} - \alpha_{Ls} z\right] \qquad (9)$$

Where P_{so} and P_{po} denotes to the input signal and pump power, respectively. This means that $P_{po}= P_{poF}$ in case of forward pump and $P_{po}=P_{poB}$ in case of backward pump, and L_{eff}, is the effective length in km, over which the nonlinearities still holds or SRS occurs in the fiber and is defined as (de Matos et al., 2003):

$$L_{eff} = \frac{1-\exp(-\alpha_{Lp}\, z)}{\alpha_{Lp}} \qquad (10)$$

Recently, there have been many efforts to utilize fiber Raman amplifier (FRA) in long-distance, high capacity wavelength division multiplexing (WDM) systems. This is mainly because FRA can improve the optical signal to noise ratio (OSNR) and reduce the impacts of fiber nonlinearities (Son et al., 2005).

SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In the present study, the optical distributed Raman amplifiers have been modeled and have been parametrically investigated, based on the coupled differential equations of first order, and also based on the set of the assumed of affecting operating parameters on the system model. In fact, the employed software computed the variables under the following operating parameters as shown in Table 1.

The following points of discussion will cover the entire operating design parameters of multiplexing/demultiplexing based optical distributed Raman amplifier device, such as, input signal power, input pumping power, operating signal wavelength, operating pump wavelength, and different fiber link media. Then, based on the basic model analysis and the set of series of the figures shown in this study, the following facts can be obtained:

Variations of the output pumping power, P_p

Variation of the output pumping power, P_p is investigated against variations of the controlling set of parameters as shown in Figures 1 to 4. Figures 1 to 4 clarify the results as follows:

A) In case of forward direction:

1) As distance z increases, the output pumping power decreases exponentially.
2) For certain value of distance z, with increasing the initial pumping power, the output pumping power also will increase.

B) In case of backward direction:

1) As distance z increases, the output pumping power increases exponentially.
2) For certain value of distance z, with increasing the

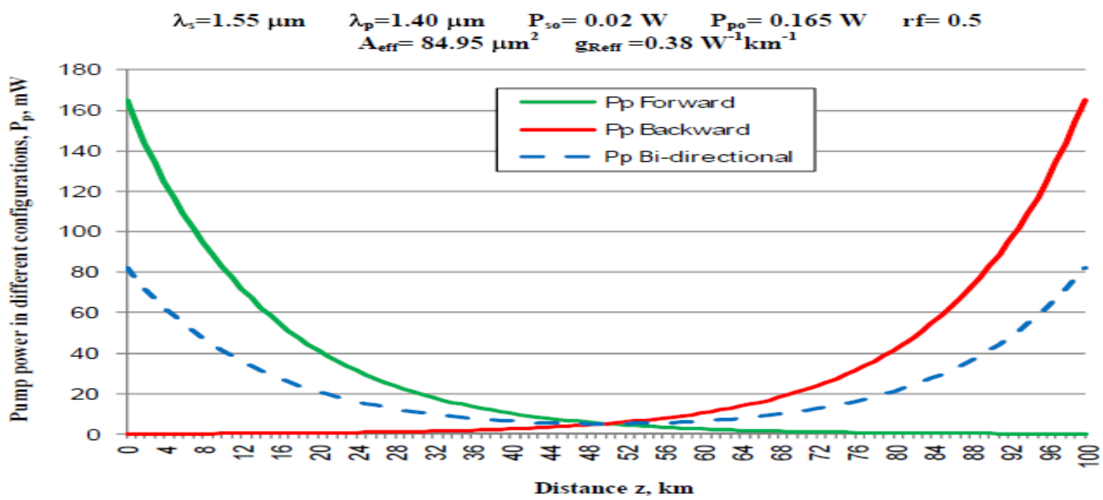

Figure 1. Variations of pump power in different configurations against variations of distance at the assumed set of the operating parameters.

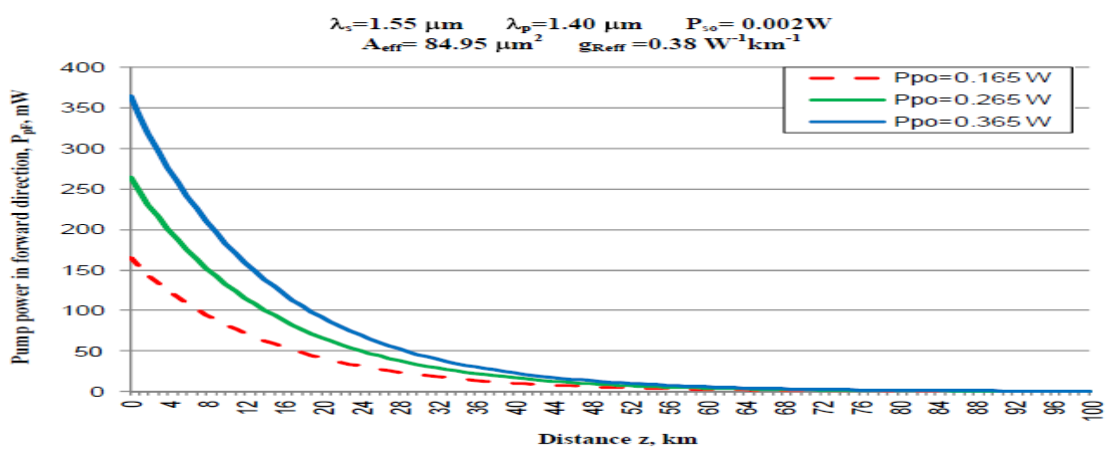

Figure 2. Variations of pump power in forward direction against variations of distance z at the assumed set of the operating parameters.

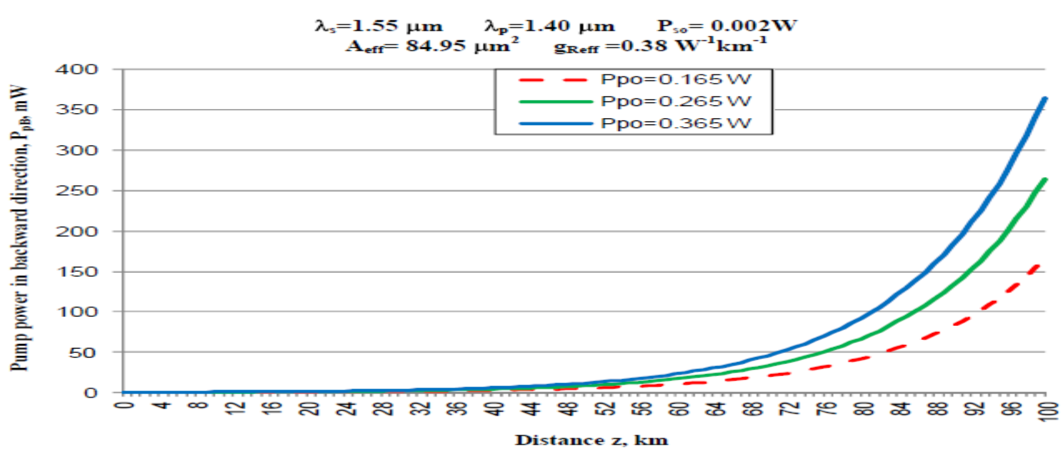

Figure 3. Variations of pump power in backward direction against variations of distance z at the assumed set of the operating parameters.

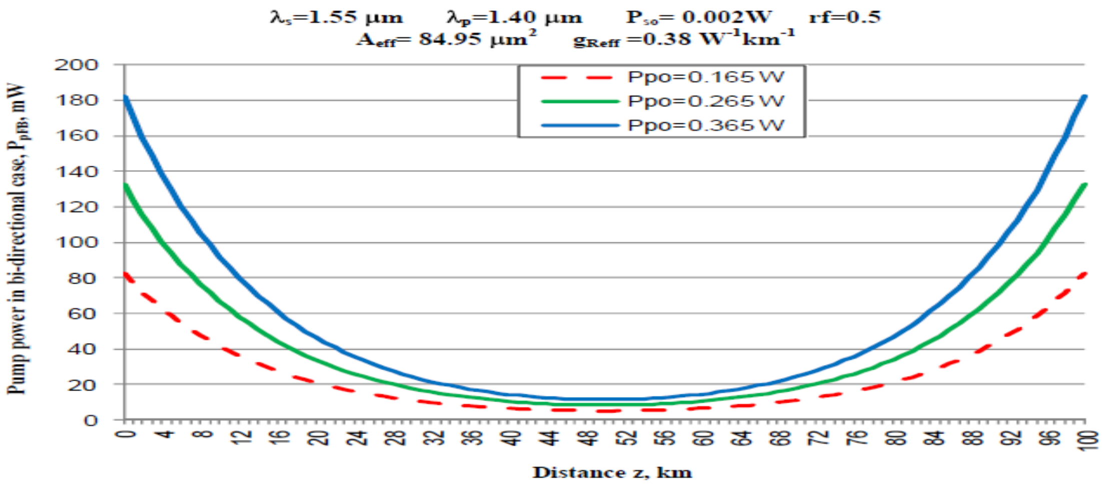

Figure 4. Variations of pump power in bi-directional case against variations of distance z at the assumed set of the operating parameters.

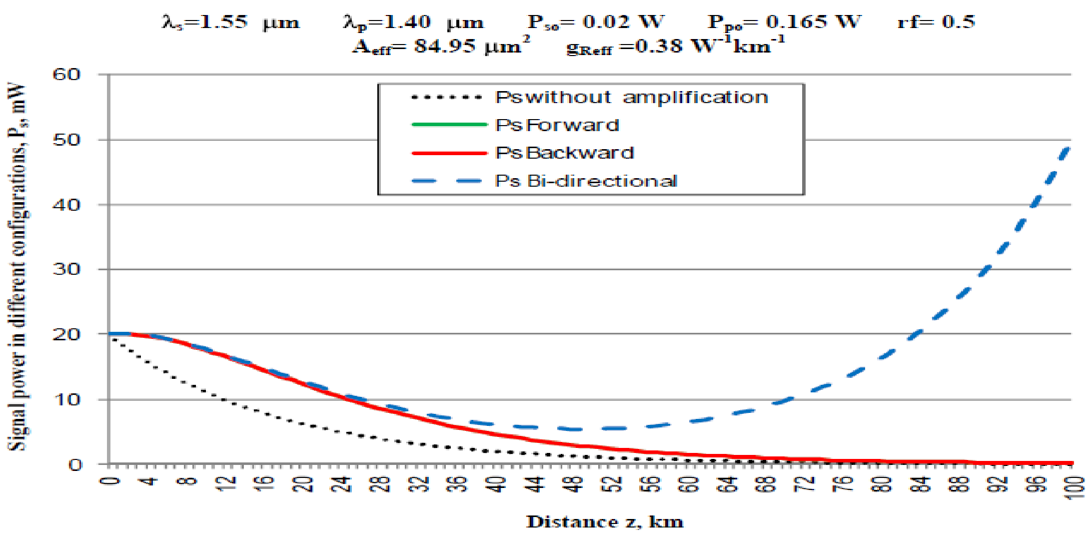

Figure 5. Variations of signal power in different configurations against variations of distance z at the assumed set of the operating parameters.

initial pumping power, the output pumping power also will increase.

C) In case of bidirectional:

1) For z ≤ 50 km, the output pumping power decreases exponentially, and for z ≥ 50 km, P_{pFB} increases exponentially.

2) For certain value of distance z, with increasing the initial pumping power, the output pumping power also will increase.

Variations of the output signal power, P_s

Variation of the output signal power, P_s is investigated against variations of the controlling set of parameters as shown in Figures 5 to 11. Figures 5 to 11 clarify the results as follows:

A) Without any amplification: with increasing distance, z, the output signal power decreases exponentially.

B) In case of forward direction:

1) For certain value of initial pumping power:

i) Initial pumping power = 0.165 mW, for distance z ≤ 2 km, the output signal power increases exponentially, and for z ≥ 2 km, the output signal power decreases exponentially.

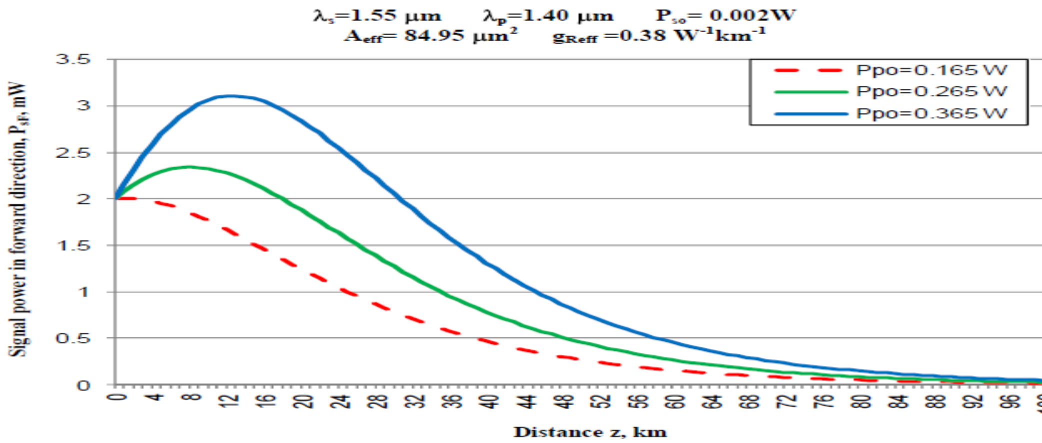

Figure 6. Variations of signal power in forward direction against variations of distance z at the assumed set of the operating parameters.

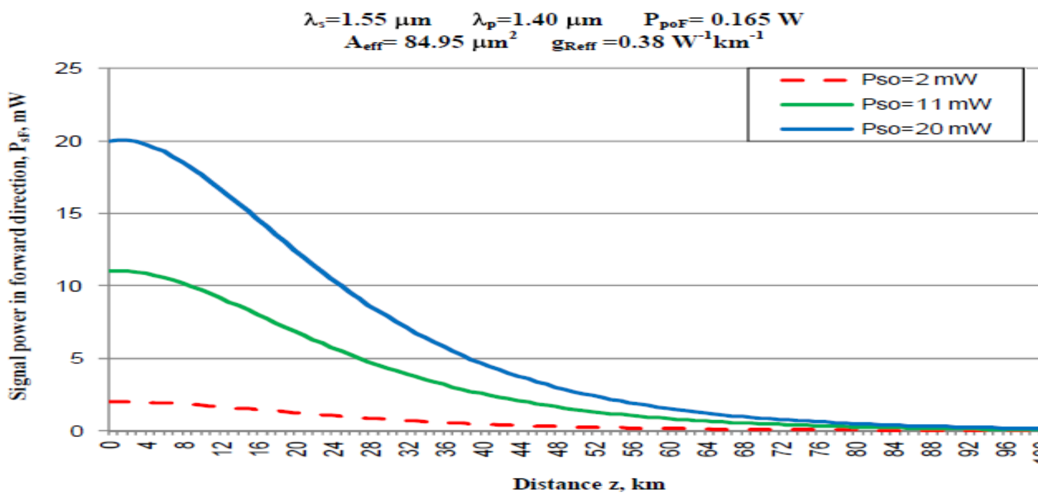

Figure 7. Variations of signal power in forward direction against variations of distance z at the assumed set of the operating parameters.

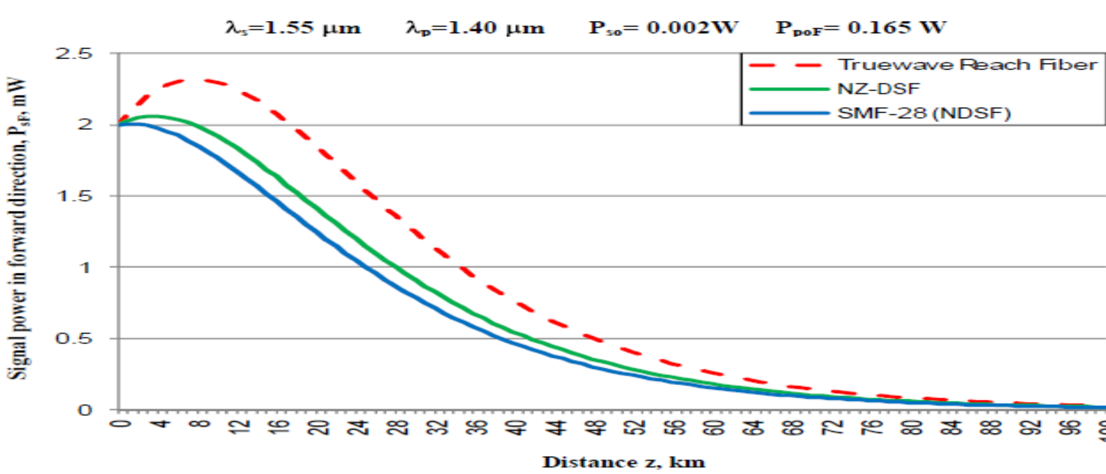

Figure 8. Variations of signal power in forward direction against variations of distance z at the assumed set of the operating parameters.

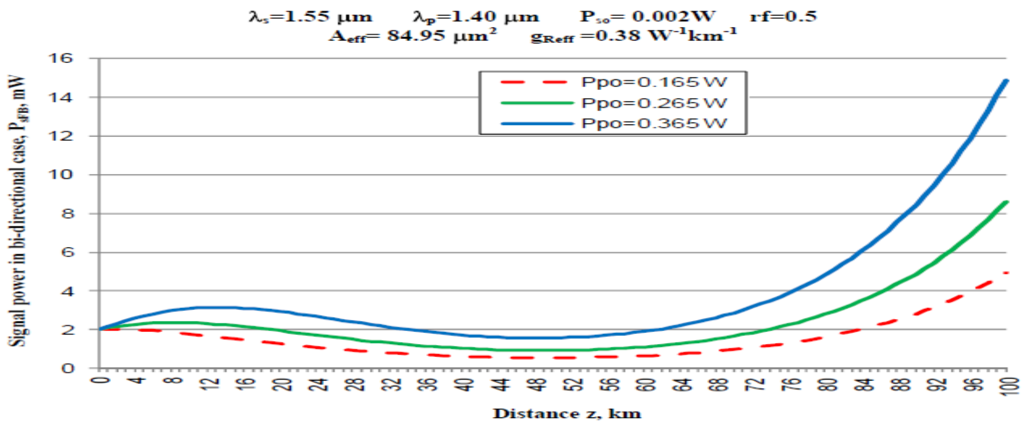

Figure 9. Variations of signal power in bi-directional case against variations of distance z at the assumed set of the operating parameters.

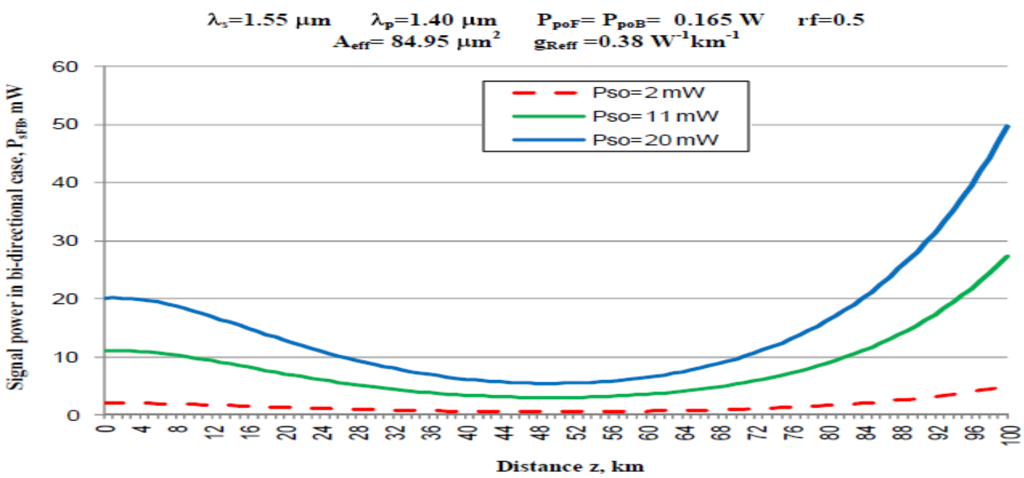

Figure 10. Variations of signal power in case of bi-directional case against variations of distance z at the assumed set of the operating parameters.

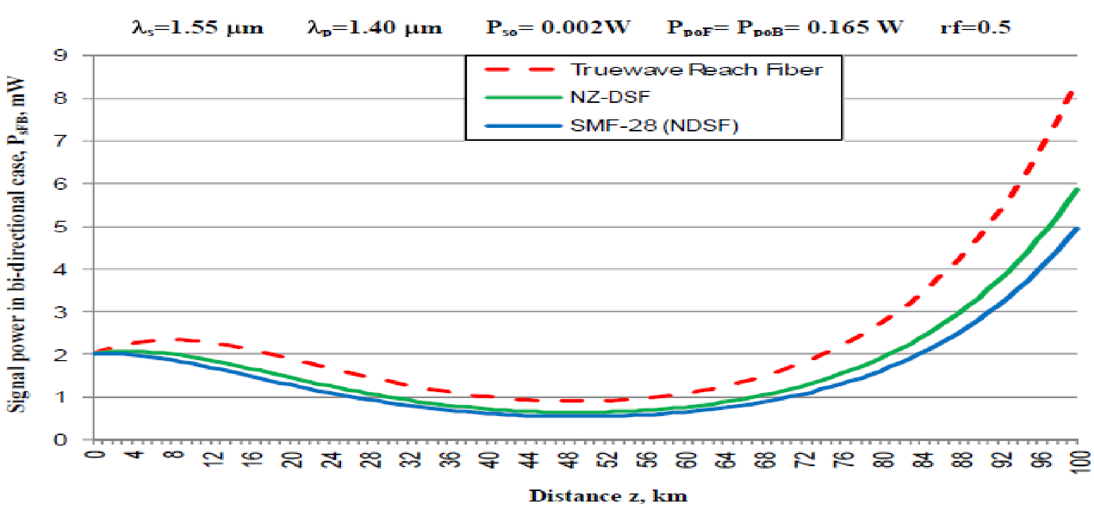

Figure 11. Variations of signal power in bi-directional case against variations of distance z at the assumed set of the operating parameters.

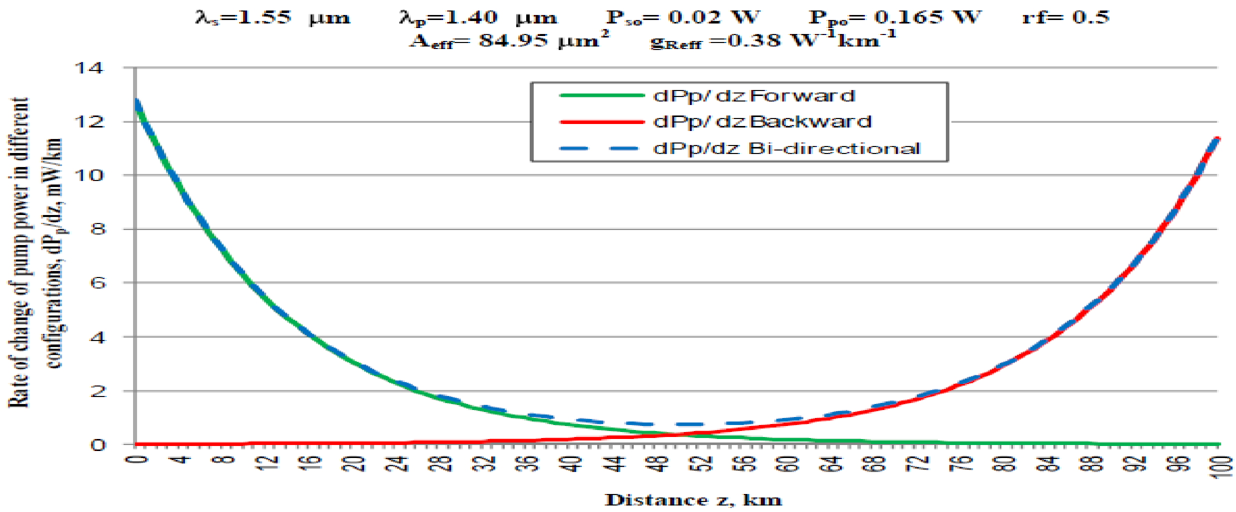

Figure 12. Variations of rate of change of pump power in different configurations against variations of distance z at the assumed set of the operating parameters.

ii) Initial pumping power = 0.265 mW, for distance z ≤ 8 km, the output signal power increases exponentially, and for z ≥ 8 km, the output signal power decreases exponentially.
iii) Initial pumping power = 0.365 mW, for distance z ≤ 13 km, the output signal power increases exponentially, and for z ≥ 13 km, the output signal power decreases exponentially.
2) For certain value of distance z:

i) With increasing the initial pumping power, the output signal power also will increase.
ii) With increasing the initial signal power, the output signal power also will increase.
3) After using different media of optical fiber cable, it is indicated that the true wave reach fiber presented the best results.
C) In case of backward direction:

The results are the same as in case of forward direction.
D) In case of bidirectional:

1) For certain value of initial pumping power:

i) Initial pumping power = 0.165 W, for distance z ≤ 1 km, the output signal power increases exponentially, for 1 ≤ z, km ≤ 50 the output signal power decreases exponentially, and for z ≥ 50 km, the output signal power increases exponentially again.
ii) Initial pumping power = 0.265 W, for distance z ≤ 8 km, the output signal power increases exponentially, for 8 ≤ z, km ≤ 49 the output signal power decreases exponentially, and for z ≥ 49 km, the output signal power increases exponentially again.
iii) Initial pumping power = 0.365 W, for distance z ≤ 13 km, the output signal power increases exponentially, for 13 ≤ z, km ≤ 48 the output signal power decreases exponentially, and for z ≥ 48 km, the output signal power increases exponentially again.
2) For certain value of distance z:

i) With increasing the initial signal power, the output signal power also will increase.
ii) With increasing the initial pumping power, the output signal power also will increase.
3) After using different media of optical fiber cable, it is indicated that the true wave reach fiber presented the best results.

Variations of rate of change of pump power, dP_p/dz

Variation of the rate of change of pump power in different configurations; dP_p/dz is investigated against variations of the controlling set of parameters as shown in Figures 12 to 17. Figures 12 to 17 clarify the results as follows:

A) In case of forward direction:

1) As distance z increases, dP_{pF}/dz decreases exponentially.
2) For certain value of distance z, with increasing the initial pumping power, dP_{pF}/dz also will increase.
3) For certain value of distance z, with increasing the initial signal power, dP_{pF}/dz also will increase
B) In case of backward direction:

1) As distance z increases, dP_{pB}/dz increases exponentially.
2) For certain value of distance z, with increasing the initial pumping power, dP_{pB}/dz also will increase.
C) In case of bidirectional:

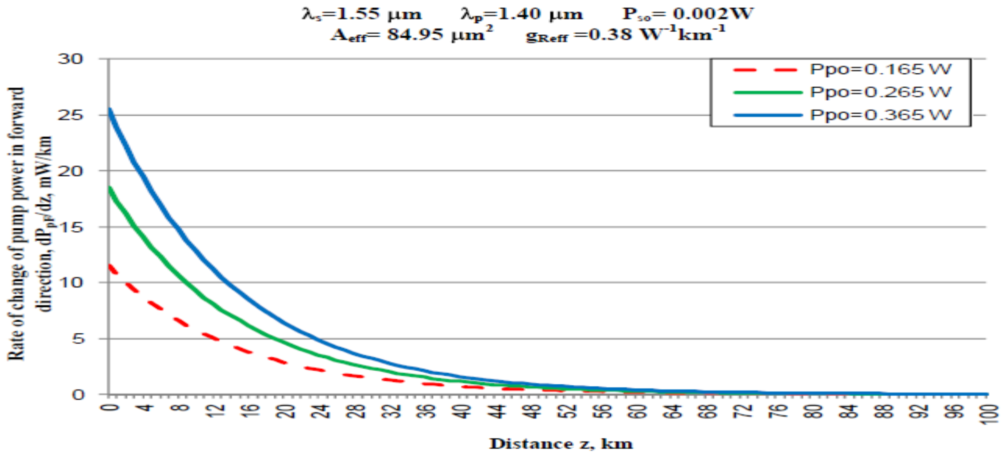

Figure 13. Variations of rate of change of pump power in forward direction against variations of distance z at the assumed set of the operating parameters.

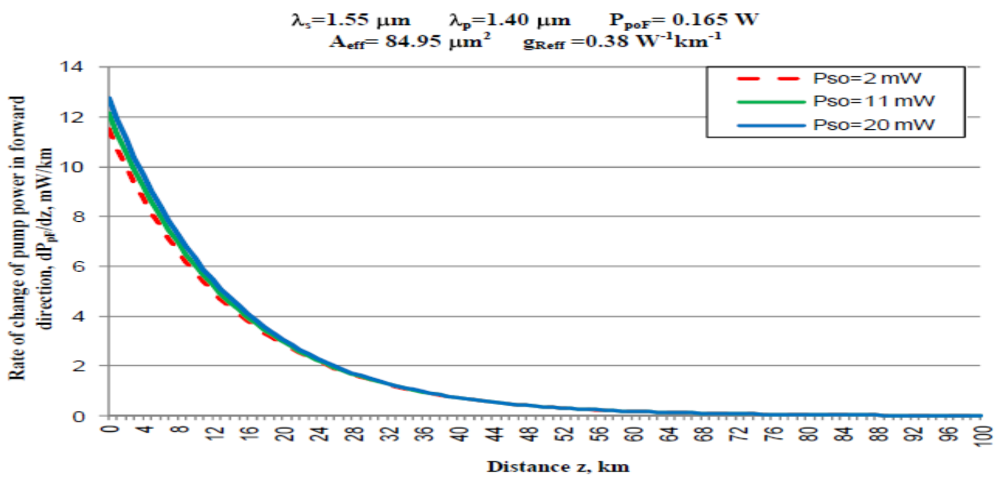

Figure 14. Variations of rate of change of pump power in forward direction against variations of distance z at the assumed set of the operating parameters.

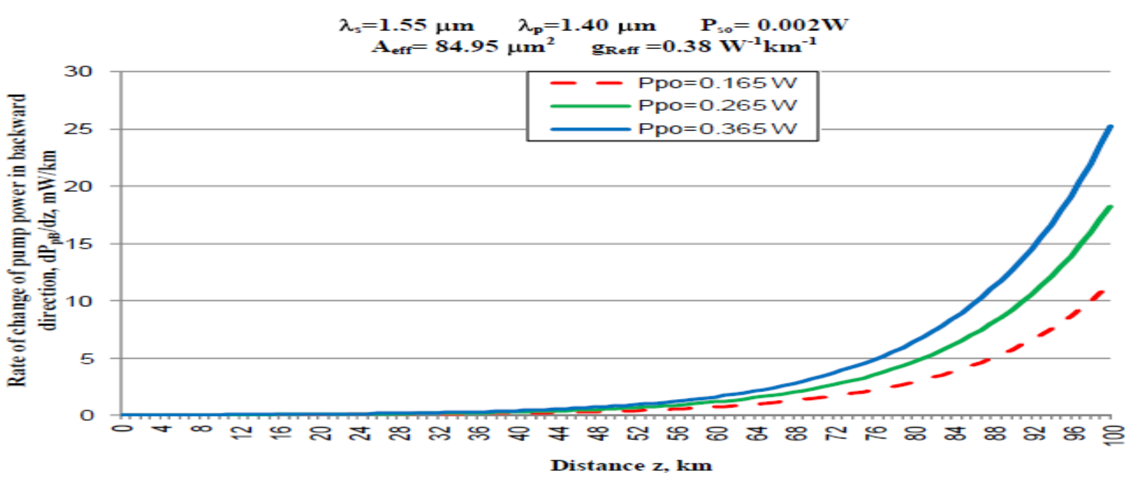

Figure 15. Variations of rate of change of pump power in backward direction against variations of distance z at the assumed set of the operating parameters.

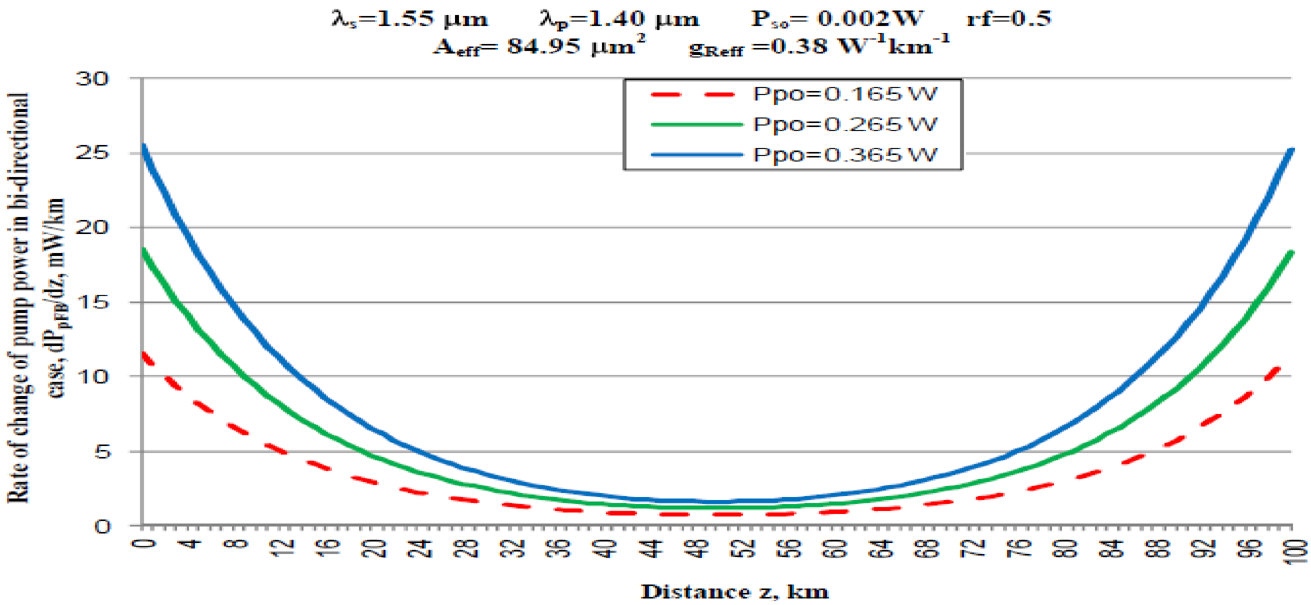

Figure 16. Variations of rate of change of pump power in bi-directional case against variations of distance z at the assumed set of the operating parameters.

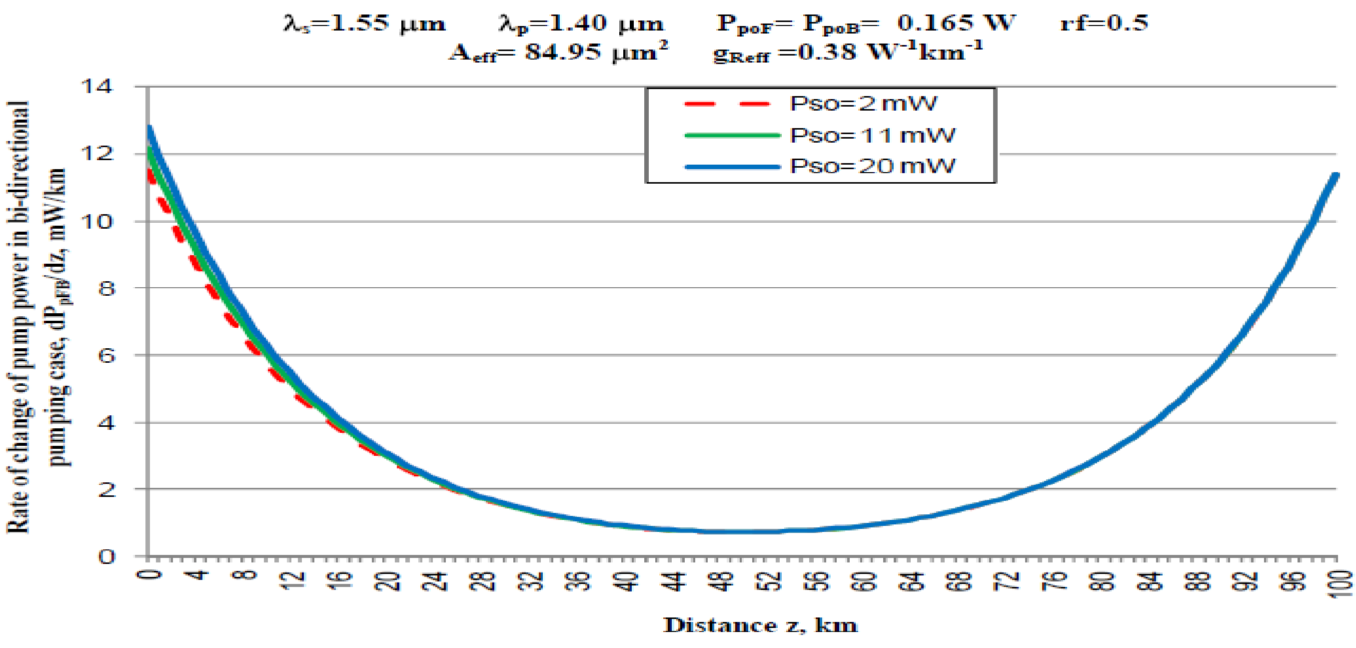

Figure 17. Variations of rate of change of pump power in bi-directional pumping case against variations of distance z at the assumed set of the operating parameters

1) For $z \leq 50$ km, dP_{pFB}/dz decreases exponentially, and for $z \geq 50$ km, dP_{pFB}/dz increases exponentially.
2) For certain value of distance z, with increasing the initial pumping power, dP_{pFB}/dz also will increase.
3) For certain value of distance z, with increasing the initial signal power, dP_{pFB}/dz also will increase.

Variations of rate of change of signal power, dP_s/dz

Variation of the rate of change of signal power in different configurations; dP_s/dz is investigated against variations of the controlling set of parameters as shown in Figures 18 to 31. Figures 18 to 31 clarify the results as follows:

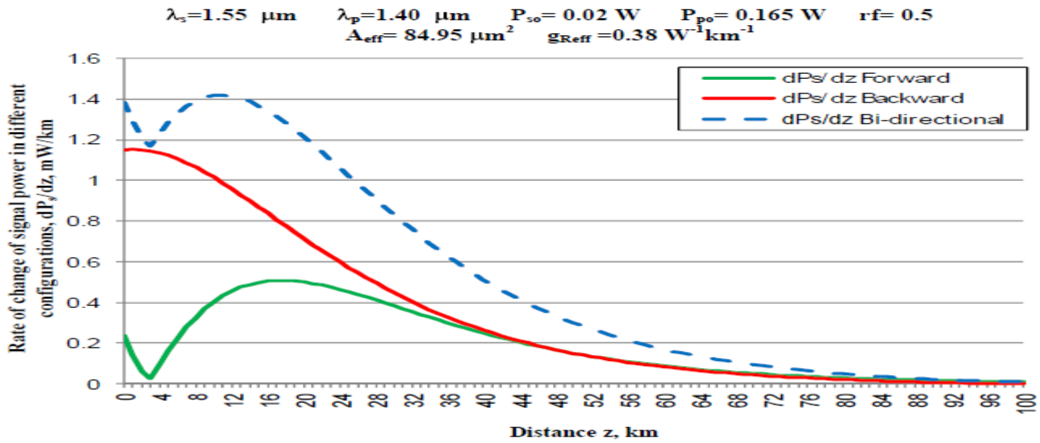

Figure 18. Variations of rate of change of signal power in different configurations against variations of distance z at the assumed set of the operating parameters.

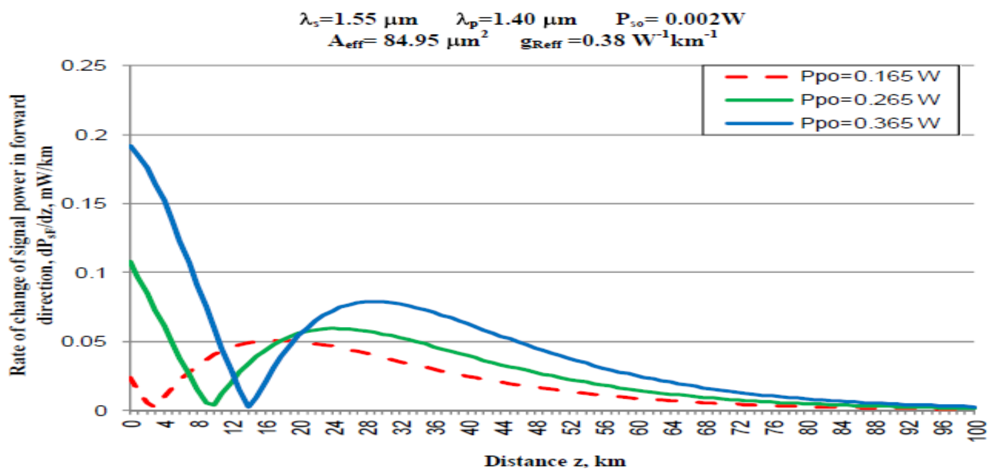

Figure 19. Variations of rate of change of signal power in forward direction against variations of distance z at the assumed set of the operating parameters.

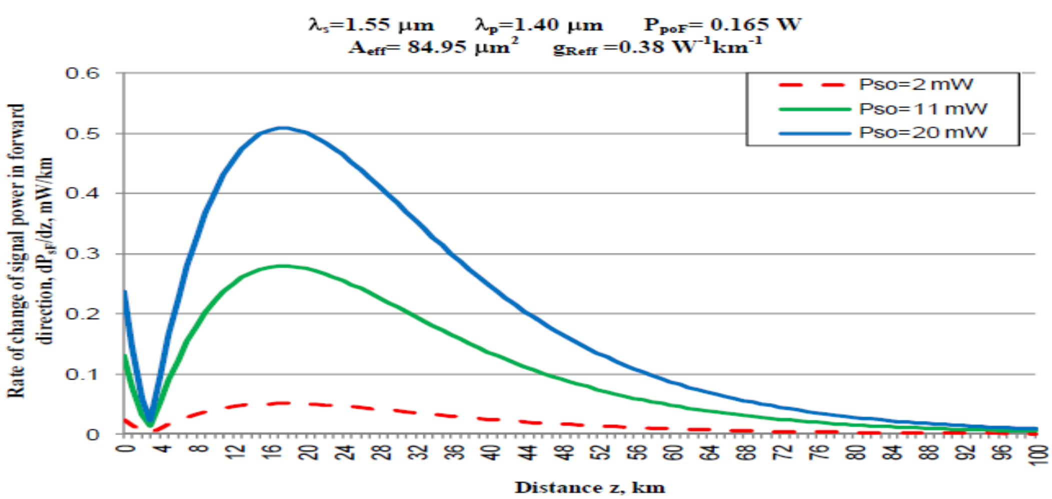

Figure 20. Variations of rate of change of signal power in forward direction against variations of distance z at the assumed set of the operating parameters.

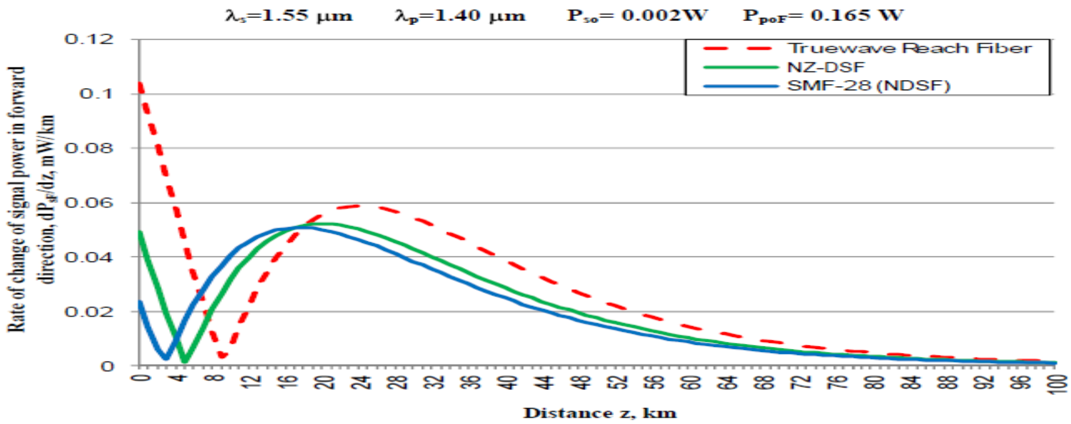

Figure 21. Variations of rate of change of signal power in forward direction against variations of distance z at the assumed set of the operating parameters.

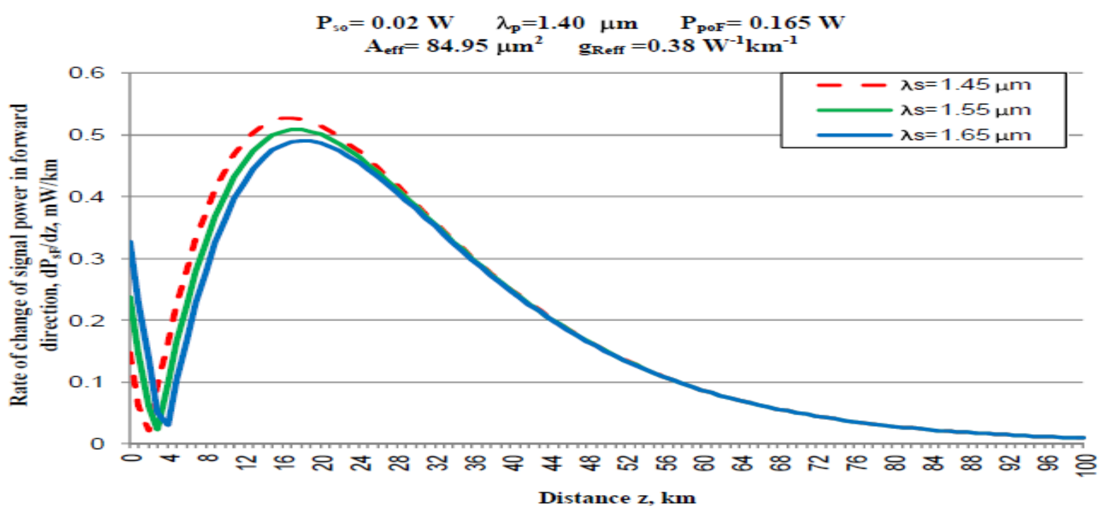

Figure 22. Variations of rate of change of signal power in forward direction against variations of distance z at the assumed set of the operating parameters.

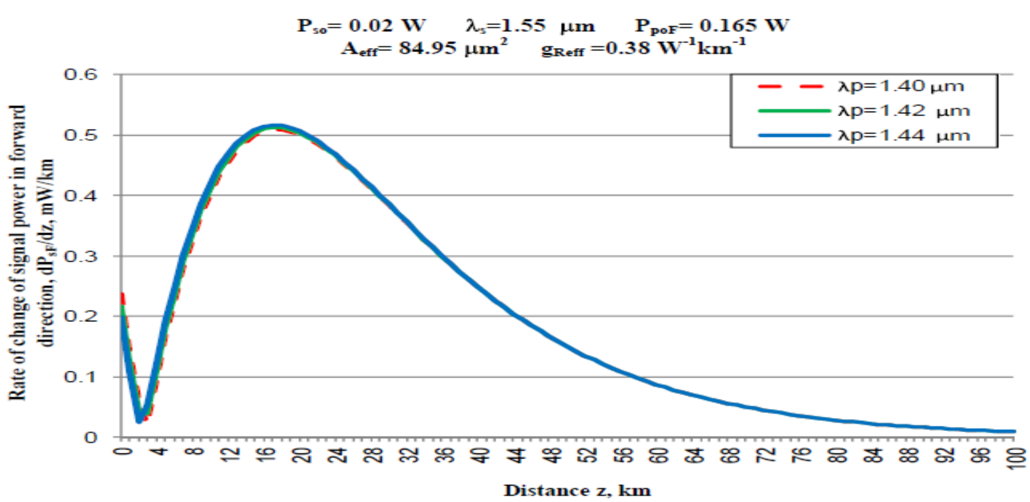

Figure 23. Variations of rate of change of signal power in forward direction against variations of distance z at the assumed set of the operating parameters

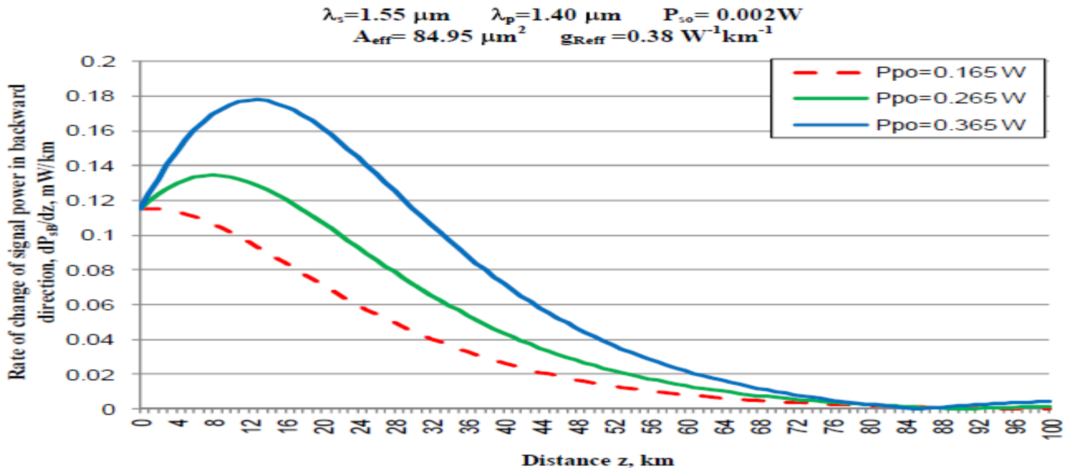

Figure 24. Variations of rate of change of signal power in backward direction against variations of distance z at the assumed set of the operating parameters.

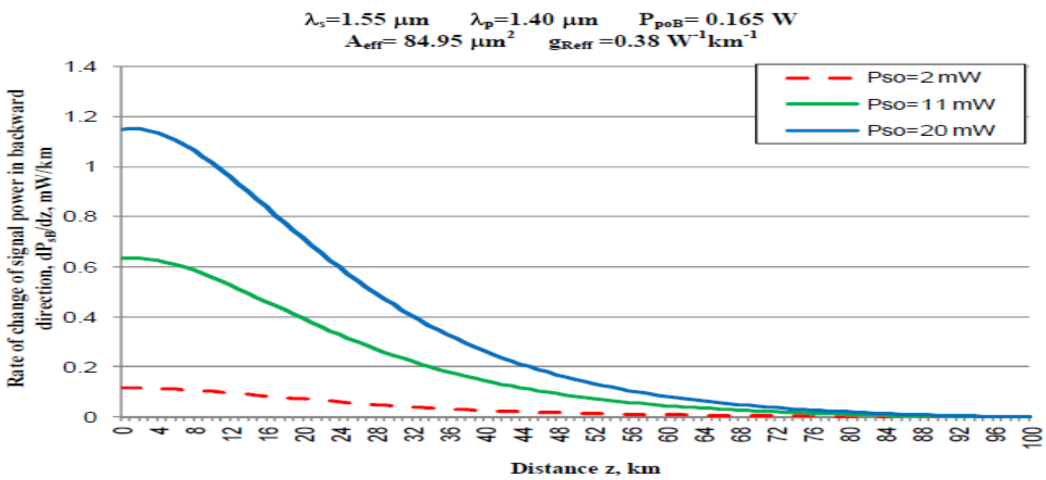

Figure 25. Variations of rate of change of signal power in backward direction against variations of distance z at the assumed set of the operating parameters.

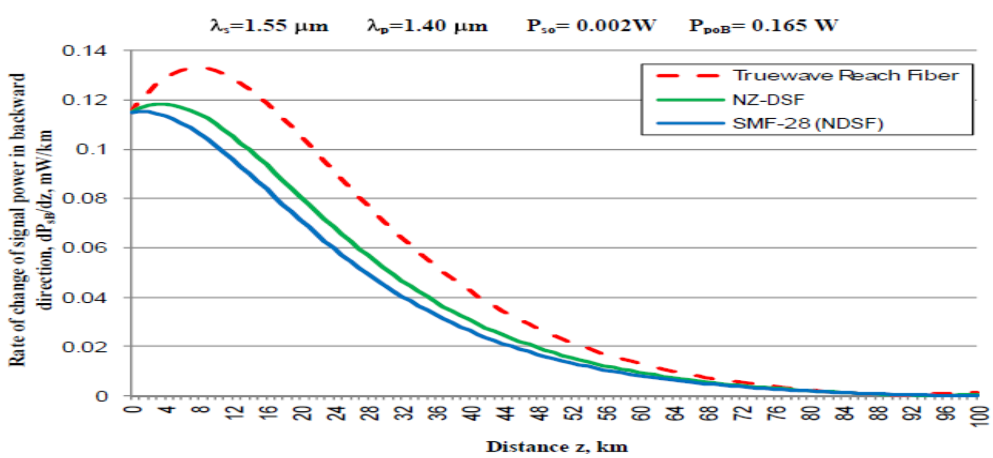

Figure 26. Variations of rate of change of signal power in backward direction against variations of distance z at the assumed set of the operating parameters.

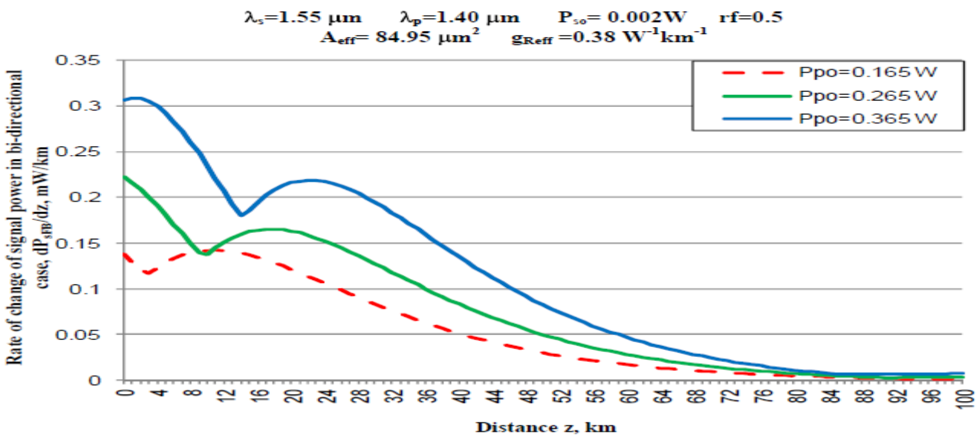

Figure 27. Variations of rate of change of signal power in bi-directional case against variations of distance z at the assumed set of the operating parameters.

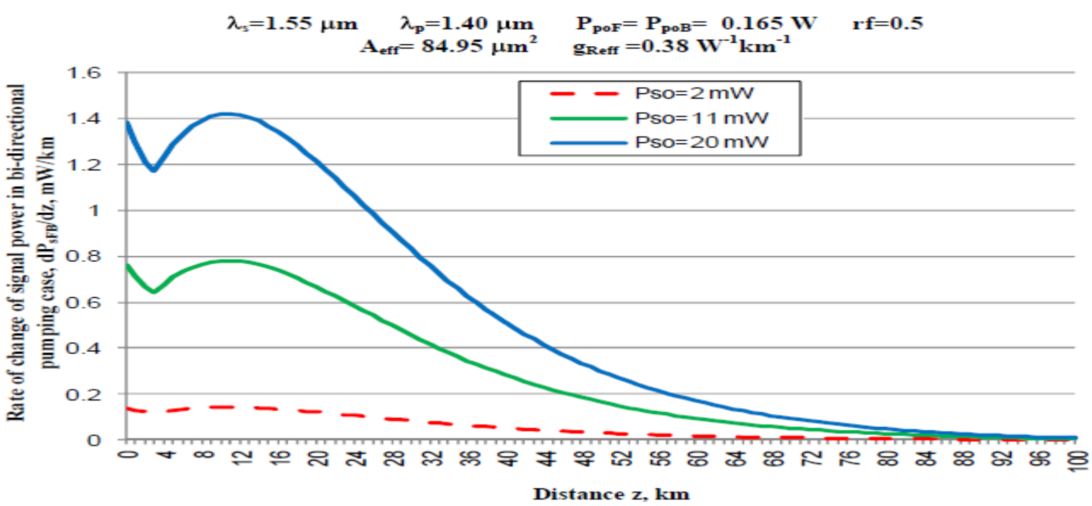

Figure 28. Variations of rate of change of signal power in bi-directional pumping case against variations of distance z at the assumed set of the operating parameters.

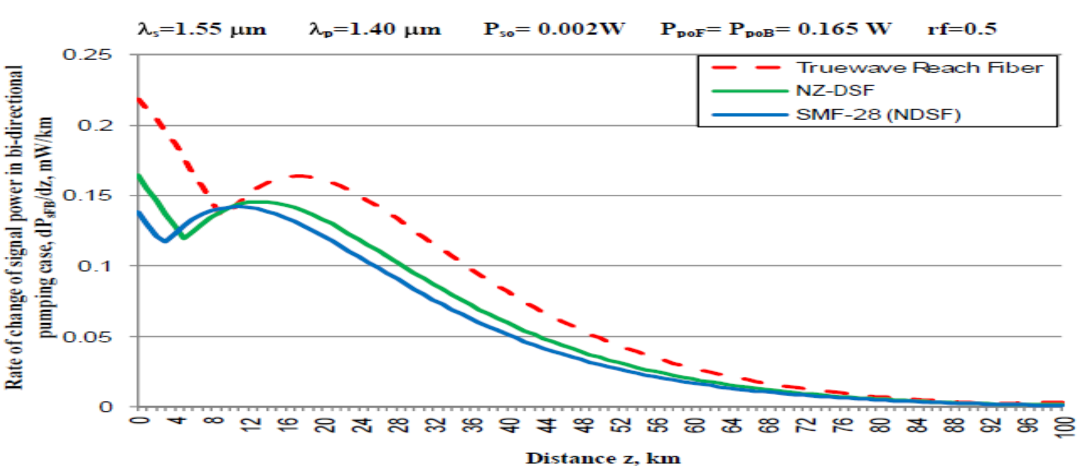

Figure 29. Variations of rate of change of signal power in bi-directional pumping case against variations of distance z at the assumed set of the operating parameters.

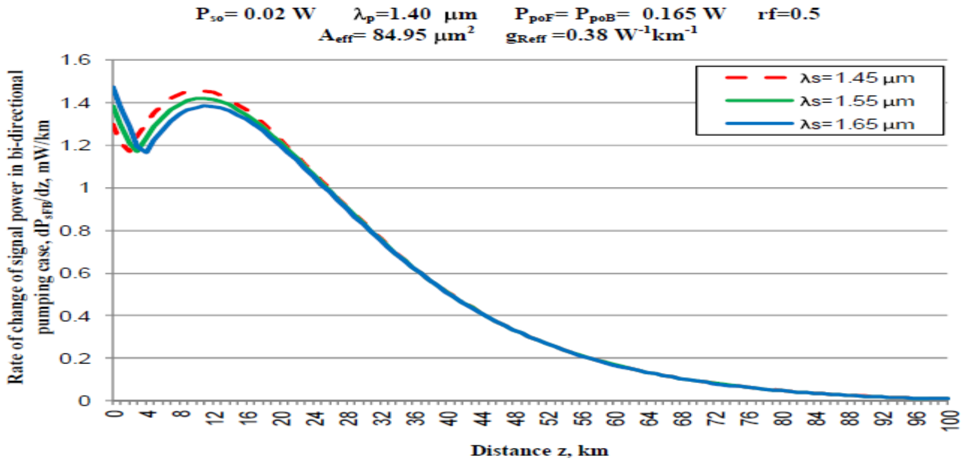

Figure 30. Variations of rate of change of signal power in bi-directional pumping case against variations of distance z at the assumed set of the operating parameters.

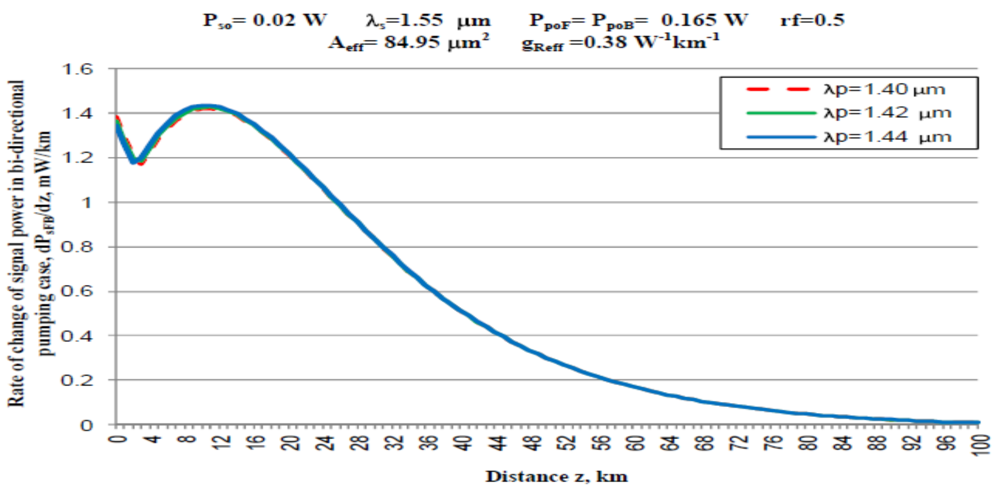

Figure 31. Variations of rate of change of signal power in bi-directional pumping case against variations of distance z at the assumed set of the operating parameters.

A) In case of forward direction:
1) For certain value of initial pumping power:

i) Initial pumping power = 0.165 W, for 0 ≤ z, km ≤ 3, dP_{sF}/dz decreases linearly, for 3 ≤ z, km ≤ 18, dP_{sF}/dz increases exponentially, and for z ≥ 18 km, dP_{sF}/dz decreases exponentially.
ii) Initial pumping power = 0.265 W, for 0 ≤ z, km ≤ 10, dP_{sF}/dz decreases linearly, for 10 ≤ z, km ≤ 24, dP_{sF}/dz increases exponentially, for z ≥ 24 km, dP_{sF}/dz decreases exponentially.
iii) Initial pumping power = 0.365 W, for 0 ≤ z, km ≤ 14, dP_{sF}/dz decreases linearly, for 14 ≤ z, km ≤ 29, dP_{sF}/dz increases exponentially, for z ≥ 29 km, dP_{sF}/dz decreases exponentially.

2) For any value of initial signal power: for 0 ≤ z, km ≤ 3, dP_{sF}/dz decreases linearly, for 3 ≤ z, km ≤ 18, dP_{sF}/dz increases exponentially, and for z ≥ 18 km, dP_{sF}/dz decreases exponentially.
3) For certain value of distance, z:

i) With increasing the initial signal power, dP_{pF}/dz also will increase.
ii) With increasing the initial pumping power, dP_{pF}/dz also will increase.
4) For certain value operating signal wavelength, λ_s:

i) λ_s = 1.45 μm, for 0 ≤ z, km ≤ 2, dPs_F/dz decreases linearly, for 2 ≤ z, km ≤ 17, dPsF/dz increases exponentially, and for z ≥ 17 km, dPs_F/dz decreases exponentially.
ii) λ_s = 1.55 μm, for 0 ≤ z, km ≤ 3, dPs_F/dz decreases linearly, for 3 ≤ z, km ≤ 18, dPsF/dz increases

exponentially, and for z ≥ 18 km, dPs_F/dz decreases exponentially.
iii) λ_s = 1.65 μm for 0 ≤ z, km ≤ 4, dPs_F/dz decreases linearly, for 4 ≤ z, km ≤ 19, dPsF/dz increases exponentially, and for z ≥ 19 km, dPs_F/dz decreases exponentially.
5) At the beginning with increasing the operating signal wavelength, λ_s dP_{sF}/dz also will increase, after that dP_{sF}/dz decreases with increasing the operating signal wavelength, λ_s.
6) For certain value operating pump wavelength, λ_p:

i) λ_p = 1.40 μm, for 0 ≤ z, km ≤ 3, dPs_F/dz decreases linearly, for 3 ≤ z, km ≤ 18, dPsF/dz increases exponentially, and for z ≥ 18 km, dPs_F/dz decreases exponentially.
ii) λ_p = 1.42 μm, for 0 ≤ z, km ≤ 2, dPs_F/dz decreases linearly, for 2 ≤ z, km ≤ 17, dPsF/dz increases exponentially, and for z ≥ 17 km, dPs_F/dz decreases exponentially.
iii) λ_p = 1.44 μm for 0 ≤ z, km ≤ 1, dPs_F/dz decreases linearly, for 1 ≤ z, km ≤ 16, dPsF/dz increases exponentially, and for z ≥ 16 km, dPs_F/dz decreases exponentially.
7) After using different media of optical fiber cable, it is indicated that the true wave reach fiber presented the best results.
B) In case of backward direction:

1) For certain value of initial pumping power:

i) Initial pumping power = 0.165 mW, for distance z ≤ 2 km, dP_{sB}/dz increases exponentially, and for z ≥ 2 km, dP_{sB}/dz decreases exponentially.
ii) Initial pumping power = 0.265 mW, for distance z ≤ 8 km, dP_{sB}/dz increases exponentially, and for z ≥ 8 km, dP_{sB}/dz decreases exponentially.
iii) Initial pumping power = 0.365 mW, for distance z ≤ 13 km, dP_{sB}/dz increases exponentially, and for z ≥ 13 km, dP_{sB}/dz decreases exponentially.
2) For certain value of distance z:

i) With increasing the initial pumping power, dP_{sB}/dz also will increase.
Ii) With increasing the initial signal power, dP_{sB}/dz also will increase.
3) After using different media of optical fiber cable, it is indicated that the true wave reach fiber presented the best results.
C) In case of bi-directional:

1) For certain value of initial pumping power:

i) Initial pumping power = 0.165 W, for 0 ≤ z, km ≤ 3, dP_{sFB}/dz decreases linearly, for 3 ≤ z, km ≤ 11, dP_{sFB}/dz increases exponentially, and for z ≥ 11 km, dP_{sFB}/dz decreases exponentially.
ii) Initial pumping power = 0.265 W, for 0 ≤ z, km ≤ 10, dP_{sFB}/dz decreases linearly, for 10 ≤ z, km ≤ 18, dP_{sFB}/dz increases exponentially, for z ≥ 18 km, dP_{sFB}/dz decreases exponentially.
iii) Initial pumping power = 0.365 W, for 0 ≤ z, km ≤ 14, dP_{sFB}/dz decreases linearly, for 14 ≤ z, km ≤ 22, dP_{sFB}/dz increases exponentially, for z ≥ 22 km, dP_{sFB}/dzs decreases exponentially.
2) For any value of initial signal power: for 0 ≤ z, km ≤ 3, dP_{sFB}/dz decreases linearly, for 3 ≤ z, km ≤ 11, dP_{sFB}/dz increases exponentially, and for z ≥ 11 km, dP_{sFB}/dz decreases exponentially.
3) For certain value of distance, z:

i) With increasing the initial signal power, dP_{sFB}/dz also will increase.
ii) With increasing the initial pumping power, dP_{sFB}/dz also will increase.
4) For certain value operating signal wavelength, λ_s:

i) λ_s = 1.45 μm, for 0 ≤ z, km ≤ 2, dP_{sFB}/dz decreases linearly, for 2 ≤ z, km ≤ 10, dP_{sFB}/dz increases exponentially, and for z ≥ 10 km, dP_{sFB}/dz decreases exponentially.
ii) λ_s = 1.55 μm, for 0 ≤ z, km ≤ 3, dP_{sFB}/dz decreases linearly, for 3 ≤ z, km ≤ 11, dP_{sFB}/dz increases exponentially, and for z ≥ 11 km, dP_{sFB}/dz decreases exponentially.
iii) λ_s = 1.65 μm for 0 ≤ z, km ≤ 4, dP_{sFB}/dz decreases linearly, for 4 ≤ z, km ≤ 12, dP_{sFB}/dz increases exponentially, and for z ≥ 12 km, dP_{sFB}/dz decreases exponentially.
5) At the beginning with increasing the operating signal wavelength, λ_s dPs_{FB}/dz also will increase, after that dPs_{FB}/dz decreases with increasing the operating signal wavelength, λ_s.
6) For certain value operating pump wavelength, λ_p:

i) λ_p = 1.40 μm, for 0 ≤ z, km ≤ 3, dP_{sFB}/dz decreases linearly, for 3 ≤ z, km ≤ 11, dP_{sFB}/dz increases exponentially, and for z ≥ 11 km, dP_{sFB}/dz decreases exponentially.
ii) λ_p = 1.42 μm, for 0 ≤ z, km ≤ 2, dP_{sFB}/dz decreases linearly, for 2 ≤ z, km ≤ 11, dP_{sFB}/dz increases exponentially, and for z ≥ 11 km, dP_{sFB}/dz decreases exponentially.
iii) λ_p = 1.44 μm for 0 ≤ z, km ≤ 1, dP_{sFB}/dz decreases linearly, for 1 ≤ z, km ≤ 11, dP_{sFB}/dz increases exponentially, and for z ≥ 11 km, dP_{sFB}/dz decreases exponentially. After using different media of optical fiber cable, it is indicated that the true wave reach fiber presented the best results.

Conclusions

The points of discussion indicated all the operating design parameters of multiplexing/demultiplexing based distributed optical FRA device, such as input signal power, input pumping power, operating signal wavelength, operating pump wavelength and different fiber link media. Therefore, we have deeply investigated multiplexing/demultiplexing based distributed optical FRA over wide range of the affecting parameters**.** As well as we have taken into account signal power, pumping power, and the rate of change of both signal power and pumping power along the transmission distance within the variety of operating signal wavelength, operation pumping wavelength, input signal power, input pumping power, different fiber link media, and finally Raman gain efficiency for all pumping direction configurations such as forward, backward and bidirectional pumping. The effects of the verity of these parameters were previously mentioned in details. After using different media of optical fiber cable, it is indicated that the true wave reach fiber presented the best candidate media for the highest signal transmission performance efficiency.

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