An Optimization Process for Hybrid Dual-Stage Raman/EDF Amplifiers When Kerr-Nonlinearity, Double Rayleigh Backscattering Noise and OSNR are Important

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SUMMARY In this paper, a detailed model of a hybrid dual-stage Raman/erbium-doped fiber (EDF) amplifier is presented. This model takes into account the impact of double Rayleigh backscattering (DRB) noise, amplified spontaneous emission (ASE) noise and Kerr-nonlinearity induced impairments in the amplification process. Using this model, we present a comprehensive analysis of the operation of hybrid dual-stage Raman/EDF amplifiers under above impairments. We show that under fixed total gain conditions for the amplifier module, high Raman gain causes the introduction of increased DRB noise to the amplified signals whereas low Raman gain causes the introduction of high ASE noise power through EDF amplifier. Therefore a balance between the Raman amplifier gain and EDF amplifier gain is required for optimal operation. These observations are then combined to show an optimization process, which could be applied to improve the design of hybrid dual-stage Raman/EDF amplifiers.

key words: dual-stage Raman amplifier, Rayleigh backscattering, erbium doped fiber amplifier, ASE, optimization

1. Introduction

In recent years, the massive and continuous growth of data traffic, mainly due to internet related activities has called for the increase of transmission capacity in communication networks. For the last decade or so, researchers have shown that wavelength division multiplexing (WDM) technology offers a cost effective way to increase the transmission capacity by transmitting closely spaced multiple wavelengths over a single fiber [1]. However, the number of different wavelength channels that can be launched into a single fiber is severely restricted by the fiber-attenuation based available transmission bandwidth of fiber [1], [2]. Therefore, it is very clear that by widening the gain bandwidth of the transmission link, this could at least be partially resolved [2]–[5].

A hybrid Raman/erbium doped fiber (EDF) amplifier (HFA) is one of the promising technologies to provide a widened and flattened gain-bandwidth over the commonly used transmission windows; C band (1530–1565 nm) and L band (1565–1625 nm). For instance, Kawai and Nielsen [6], [7] experimentally demonstrated a WDM system over the C+L band via HFAs enabling 900 km transmission of 14 × 2.5 Gbit/s with 60 km repeater spacing [6] and 3.28 Tb/s (82 × 40 Gb/s) transmission in a 3 × 100 km system [7]. The principle motivation behind the use of HFAs rather than passive-transmission fibers amplified by erbium-doped fiber amplifiers (EDFAs) is that such setup would provide an overall reduction of the amplified spontaneous emission (ASE) noise at the receiver end.

Due to its distributed amplification property, even at higher gain, the HFAs can be designed to minimize nonlinear impairments along transmission fiber due to high path-averaged signal power. Such nonlinear impairments are not desired because they will degrade the optical signal-to-noise ratio (OSNR) at the receiver. Therefore, researchers for years have continuously searched for optimal amplification strategies with high gain. For example, in [8], an optimal configuration of HFA was reported with successful exploitation of fiber nonlinear impairment and ASE noise for maximizing the output OSNR. However, they did not consider the homodyne crosstalk due to the double Rayleigh backscattering (DRB) of signal, which plays a significant role in the operation of distributed Raman amplifiers, especially under high gain conditions. Moreover, another recent study has shown that it is possible to design a dual-stage discrete Raman amplifier with improved OSNR by taking into account ASE, DRB noise and certain dominant nonlinear impairments [9]. Also, recently some research have been reported on optimum design of hybrid Raman/EDF amplifier considering impairments resulting from ASE noise, DRB noise and kerr nonlinearity [8], [10], [11]. Nevertheless, to the best of authors’ knowledge, no work has been reported in literature on optimum design of a hybrid dual-stage Raman/EDF amplifier considering impairments resulting from ASE noise, DRB noise and kerr nonlinearity.

In this paper, a comprehensive investigation of the impact of DRB noise on optimal configuration of HFA is carried out. Using this result, an optimum design of a hybrid dual-stage Raman/erbium-doped fiber amplifier is presented which tries to maximize OSNR when Raman gain is varied within operational limits. Thereafter a comparison of hybrid dual-stage and single-stage Raman/EDF amplifier is presented. In Sect. 2, the details of the simulation system and the associated numerical model utilized in this work is given. In Sect. 3, we carry out a comprehensive analysis of the degradation of a HFA system from DRB noise. In Sect. 4, we modified the numerical models given in Sect. 2 to simulate a hybrid dual-stage Raman/erbium-doped fiber...
amplifier system. Thereafter, the optimization process of the dual-stage system is presented and the advantages of using dual-stage Raman amplifier over single-stage Raman amplifier in HFA are discussed. Finally, we conclude this paper in Sect. 5, after summarizing the results.

2. System Design and Simulation Model

For analysis and comparison purposes on the impact of DRB noise in HFAs, the system setup reported in [8] is used in this paper. Figure 1(a) shows the schematic diagram of the long-haul hybrid single-stage Raman/EDF amplifier system. It consists of a backward pumped Raman amplifier (RA) with transmission fiber length $L$ followed by an EDFA(1), a gain-flattening filter (GFF), a dispersion compensating fiber (DCF) of length $L_{DCF}$ to completely compensate for the dispersion generated from the transmission fiber, and an EDFA(2). Figure 1(b) is the system configuration of the hybrid dual-stage Raman/EDF amplifier, which will be used in Sect. 4 to analyse the improved OSNR. The only difference between the two systems is that in the latter, the backward pumped RA is replaced by a forward pumped RA and a bi-directional pumped RA, the rest of the system remains unchanged.

In following sub sections, we present the numerical model used for the analysis of single-stage system shown in Fig. 1(a). The simulation model for the hybrid dual-stage Raman/EDF amplifier shown in Fig. 1(b) will be given in Sect. 4.

2.1 System Gain and Optical Signal-to-Noise Ratio

The HFA is set to work under transparent condition where total gain, $G_{tot}$, is assumed to completely compensate the losses:

$$ G_{tot} = G_{Ra}G_{E1}G_{E2} $$

**Fig. 1** System configuration of (a) the hybrid Raman/erbium-doped amplifier, (b) the hybrid dual-stage Raman/erbium-doped amplifier.

$$ = \frac{1}{\exp(-\alpha_s L) G_{GFF} \exp(-\alpha_{DCF} L_{DCF})} \quad (1) $$

where $G_{Ra}$ is the Raman on-off gain of the RA, $G_{E1}$ and $G_{E2}$ are the gains of EDFA(#1) and EDFA(#2), respectively, $\alpha_s$ and $\alpha_{DCF}$ are the fiber loss coefficients at the signal wavelength for the transmission fiber and the DCF, respectively, and $L_{GFF}$ is the loss induced by the GFF.

The OSNR at the end of the HFA can be written as:

$$ \text{OSNR} = \frac{P_s}{(P_{ASE} + P_{DRB})} \quad (2) $$

where $P_s$ is the input signal power, $P_{ASE}$ and $P_{DRB}$ are the total ASE and DRB noise generated in the HFA, respectively. Note that the OSNR is expressed in decibel per 0.1 nm optical bandwidth throughout the paper.

2.2 Double Rayleigh Backscattering Noise

The total DRB noise power, $P_{DRB}$, is assumed to be the sum of the double Rayleigh backscattered signal that occurs in the transmission fiber and the DCF. Due to its short length, the DRB noise generated in the EDFA is neglected in the subsequent analysis. Considering co-propagating and counter-propagating gain formulations under undepleted pump approximation and extending the work in [12], we derive the following expression for DRB noise power:

$$ P_{DRS} = r_{RS}^2 P_s \exp(\alpha_s L) G_{Ra} \times \int_0^L \int_0^\infty G^-(0, z) G^+ (z, \zeta) G^- (\zeta, L) d\zeta dz + r_{DCF}^2 P_s \exp(\alpha_{DCF} L_{DCF}) \times \int_0^{L_{DCF}} \int_0^\infty \exp(-\alpha_{DCF} (2z + L_{DCF} - 2\zeta)) d\zeta dz \quad (3) $$

where $G^-$ and $G^+$ indicate the backward and forward Raman amplification in the transmission fiber, respectively, with following definitions:

$$ G^-(0, z) = \exp \left[ -\alpha_s z + C_{Ra} P_{pb}(L) e^{-\alpha_p L} e^{\alpha_p z} - 1 \right] \quad (4) $$

$$ G^+(z, \zeta) = \exp \left[ -\alpha_s (z - \zeta) + C_{Ra} P_{pb}(L) e^{-\alpha_p L} e^{\alpha_p z} - 1 \right] \quad (5) $$

$$ G^- (\zeta, L) = \exp \left[ -\alpha_s (L - \zeta) + C_{Ra} P_{pb}(L) \frac{1 - e^{-\alpha_p (L - \zeta)}}{\alpha_p} \right] \quad (6) $$

where $r_{RS}$ and $r_{DCF}$ are the Rayleigh backscattering coefficients of the transmission fiber and the DCF, respectively, $C_{Ra}$ is the backward Raman gain coefficients, $P_{pb}(L)$ is the backward pump power at the output end of the transmission fiber and $\alpha_p$ is the transmission fiber loss coefficient at the pump wavelength.
2.3 Amplified Spontaneous Emission Noise

The total accumulated ASE noise power generated in the HFA can be written as a sum of the original contributions with modifications due to gains it experiences in the RA and the EDFAs [8]:

\[ P_{\text{ASE}} = h f B_0 \left[ n_{\text{eq-Ra}} + n_{\text{eq-EDFA}} - \gamma_{\text{Ra}} \right] e^{\alpha_1 L} + n_{\text{eq-E2}} G_{E2} \]  

(7)

where \( h \) is the Plank’s constant, \( f \) is the channel frequency, \( B_0 \) is the bandwidth over which noise is integrated, \( n_{\text{eq-Ra}} \) and \( n_{\text{eq-EDFA}} \) are the equivalent input noise factors [13] for the RA, EDFA(#1) and EDFA(#2), respectively.

The equivalent input noise factor of the RA, \( n_{\text{eq-Ra}} \), can be derived from the power spectral density of the ASE noise under the undepleted pump approximation as:

\[ n_{\text{eq-Ra}} = \frac{S_{\text{ASE}}^{\text{Ra}}}{h f G_{\text{Ra}}} = \frac{N_{\text{eq-Ra}}^{\text{ASE}}}{G_{\text{Ra}}} \]  

(8)

where \( S_{\text{ASE}}^{\text{Ra}} \) is the power spectral density of the ASE noise at the output of the RA, \( G_{\text{Ra}} \) is the Raman on-off gain, and

\[ N_{\text{eq-Ra}}^{\text{ASE}} = \exp(-\alpha_1 L) G_{\text{Ra}} \int_0^L C_{Rj} P_{\text{pf}}(0) e^{-\alpha_2 z} G_{\text{Ra}}(z) dz \]  

(9)

is the number of ASE photons at the output of the RA [14], \( C_{Rj} \) is the forward Raman gain coefficients and \( P_{\text{pf}}(0) \) is the forward pump power at the input end of the transmission fiber.

The equivalent input noise factor of the EDFAs depends on the noise figure of the EDFAs and can be written as:

\[ n_{\text{eq-EDFA}} = \frac{1}{2} \left( N_{\text{FEFDA}} - \frac{1}{G_{\text{EDFA}}} \right) \]  

(10)

where \( N_{\text{FEFDA}} \) is the noise figure of the EDFA and \( G_{\text{EDFA}} \) is the EDFA gain.

2.4 Fiber Nonlinearity and Input Signal Power

The input signal power, \( P_s \), needs to be constrained due to fiber Kerr nonlinearity to avoid impairments such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) on transmitting signals. To enable this, we quantify the effect of nonlinearity by considering the induced phase shift, \( K_{\text{nl}} \), on propagating signals:

\[ K_{\text{nl}} = \int_0 \gamma(z) P(z) dz = P_s \left( \gamma_{\text{Ra}} L_{\text{eff-Ra}} + \gamma_{\text{DCF}} L_{\text{eff-DCF}} \right) \]  

(11)

where \( \gamma_{\text{Ra}} \) and \( \gamma_{\text{DCF}} \) are the nonlinear coefficient for the transmission fiber and the DCF, respectively, with the with definitions:

\[ \gamma_{\text{Ra}} = \frac{2 \pi n_{2\text{-Ra}}}{A_{\text{eff-Ra}} L_{\text{DCF}}} \]  

\[ \gamma_{\text{DCF}} = \frac{2 \pi n_{2\text{-DCF}}}{A_{\text{eff-DCF}} L_{\text{DCF}}} \]  

(12)

In Eq. (12), \( A_{\text{eff-Ra}} \) and \( A_{\text{eff-DCF}} \) refer to effective core areas and \( n_{2\text{-Ra}} \) and \( n_{2\text{-DCF}} \) refer to nonlinear refractive index for the transmission fiber and DCF, respectively and \( L \) is the signal wavelength. The effective lengths of standard fiber, \( L_{\text{eff-Ra}} \), and DCF, \( L_{\text{eff-DCF}} \), are given by:

\[ L_{\text{eff-Ra}} = \int_0^L \exp(-\alpha_1 L) G_{\text{Ra}}(z) dz \]  

(13)

and

\[ L_{\text{eff-DCF}} = \frac{1 - \exp(-\alpha_{\text{DCF}} L_{\text{DCF}})}{\alpha_{\text{DCF}}} \]  

(14)

Eq. (11) is then used to calculate the launchable maximum input signal power by bounding the overall phase shift to a maximum value.

3. Double Rayleigh Backscattered Noise in Hybrid Raman/EDF Amplifier

In our simulation, a 100 km nonzero dispersion-shifted fiber (NZDSF) was used as the transmission fiber and a corresponding 5 km DCF was used to compensate for the dispersion. The fiber parameters used for numerical simulations throughout this paper are summarized in Table 1. The noise figure for both EDFAs was set as 4.5 dB, the GFF is assumed have a 4 dB loss and the nonlinear phase-shift was set at 1. For comparison purposes, we use the parameter set reported in [8]. Especially, the nonlinear phase shift value used in [8] is also used in our analysis. Even though this value seems quite high for normal applications, it allows us to compare and clearly illustrate some of the key concepts essential for optimal design of dual stage hybrid Raman/EDF amplifiers. It is important to note that similar trends in results as in [8] with more realistic values can be obtained by using a smaller value for the nonlinear phase-shift in practice.

The optimal configuration of the HFA is found by varying the parameters \( K_1 = G_{\text{Ra,db}} / (G_{\text{Ra,db}} + G_{\text{E1,db}}) \) (representing the ratio of RA on-off gain before the GFF) and \( K_2 = (G_{\text{Ra,db}} + G_{\text{E1,db}}) / G_{\text{tot,db}} \) (representing the ratio of

<table>
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<tr>
<th>Table 1 Fiber parameters.</th>
<th>NZDSF</th>
<th>DCF</th>
</tr>
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<td>Attenuation, @ 1550 nm a (dB/km)</td>
<td>0.2</td>
<td>0.5</td>
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<tr>
<td>Attenuation, @ 1450 nm a (dB/km)</td>
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<td>/</td>
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<tr>
<td>Rayleigh Backscattering Coefficients, r (1/km)</td>
<td>( 1.1 \times 10^{-4} )</td>
<td>( 6.42 \times 10^{-4} )</td>
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<tr>
<td>Chromatic Dispersion, D (ps/nm/km)</td>
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<td>-100</td>
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<tr>
<td>Effective Core Area, ( A_c (\mu m^2) )</td>
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<td>25</td>
</tr>
<tr>
<td>Nonlinear Refractive Index, ( n_2 (m^2/W) )</td>
<td>( 2.5 \times 10^{-20} )</td>
<td>( 2.5 \times 10^{-20} )</td>
</tr>
<tr>
<td>Raman Gain Coefficient, ( C_R (1/km/W) )</td>
<td>0.73</td>
<td>/</td>
</tr>
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overall gain before the GFF to the total gain of HFA) to maximize the OSNR. Note that $G_{Ra, dB}$, $G_{E1, dB}$ and $G_{tot, dB}$ are expressed in decibels.

Figure 2 shows the contour plot of the OSNR surface in the $(K_1, K_2)$ plan for the HFA system without taking into consideration of DRB noise. The maximum OSNR is 54.56 dB corresponding to $(K_1, K_2) = (0.95, 0.8)$, that is $G_{Ra} = 20.14$ dB, $G_{E1} = 1.06$ dB and $G_{E2} = 5.3$ dB. The OSNR increases as the Raman on-off gain increases. It is interesting note that these results agrees well with the already reported results in [8].

Figure 3 shows the contour plot of the OSNR surface in the $(K_1, K_2)$ plan for the HFA system with inclusion of both ASE and DRB noise impairments. When compared with Fig. 2, it clearly shows that the maximum OSNR has dropped from 54.56 dB to 46.09 dB and the corresponding $(K_1, K_2)$ has shifted from $(0.95, 0.8)$ to $(0.2, 0.7)$ and $G_{Ra}$. $G_{E1}$ and $G_{E2}$ have become 3.71 dB, 14.84 dB and 7.95 dB, respectively. This pattern of variation in maximum OSNR is mainly due to the fact that under high Raman gain condition, the initiation of DRB noise is stronger and the maximum launchable input signal power is lower since it is bounded by the constant phase shift. These two factors outweigh the benefit from the reduction in ASE noise power generated from the two EDFAs. Therefore, a balance occurs at $(K_1, K_2) = (0.2, 0.7)$, a lower Raman on-off gain value of 3.71 dB, where the DRB noise and the maximum launchable input signal will not outweighs the reduction in ASE noise, such that the OSNR is maximized. In the top right hand corner of Fig. 3, it shows that the OSNR is degraded by the strong DRB noise significantly under the high Raman gain condition. OSNR is less than 33 dB for an all-Raman configuration.

Some recent publications have suggested the optimum Raman-gain ratios to total gain in hybrid amplifier are typically around 50% [10]. However in Fig. 3, the Raman gain is 3.71 dB which is 14% of the total gain, much lower than these suggested values. This is mainly due to the fact that in our simulation, the nonlinear phase-shift is set at 1 radian for illustrative and/or comparison purposes (also see [8]). Therefore, the system has a large maximum input signal power causing stronger DRB noise especially under high Raman gain. As a result, the optimum Raman-gain ratio is shifted to a lower value. By relaxing these stringent requirements on nonlinear phase shift, much realistic values for gain can be obtained.

Since symmetric bi-directional pumped RA can reduce DRB noise under high gain condition [15], [16], the backward pump RA was replaced by a symmetric bi-directional pumped RA in the HFA system. The resulting contour plot of the OSNR surface in the $(K_1, K_2)$ plan is shown in Fig. 4.

The optimal configuration of HFA has shifted from $(0.2, 0.7)$ to $(0.25, 0.75)$ and the OSNR has increased from 46.09 dB...
to 46.1 dB. In the low Raman gain region (bottom left hand corner of Fig. 4), the OSNR has less than 0.5 dB improvement. However, in the high Raman gain region (top right hand corner of Fig. 4), the OSNR has improved significantly, for instance the OSNR at 0.8 Raman on-off gain ratio (ratio of Raman on-off gain to total gain) has increased from 34 dB to 43 dB. The result shows that under high Raman gain condition, a bi-directional pumped RA is preferable as it can reduce the DRB noise and improve OSNR significantly.

4. Hybrid Dual-Stage Raman/EDF Amplifier

In order to analyze the advantages of dual-stage RA over single-stage RA in HFAs, the system model shown in Fig. 1(b) is used. Since, an additional RA is added to the HFA system, the formulations already given in Eq. (3), Fig. 1(b) is used. Since, an additional RA is added to the HFA system, the formulations already given in Eq. (3), Eq. (7) and Eq. (11) need to be modified as given below:

\[
P_{DRS} = 2 P_s \frac{\exp (\alpha_s L_1)}{G_{Ra1}} \times \int_0^{L_1} \int_0^\infty G(0, z) G(z, \zeta) G(\zeta, L_1) \, d\zeta \, dz + 2 P_s \frac{\exp (\alpha_s L_2)}{G_{Ra2}} \times \int_0^{L_2} \int_0^\infty G(0, z) G(z, \zeta) G(\zeta, L_2) \, d\zeta \, dz + P_{DCF} P_\alpha \exp (\alpha_{DCF} L_{DCF}) \times \int_0^{L_{DCF}} \int_0^\infty \exp [-\alpha_{DCF} (2z + L_{DCF} - 2\zeta)] \, d\zeta \, dz \quad (15)
\]

\[
P_{ASE} = h f B_0 \times \left[ \left( \frac{n_{eq-Ra1}}{\eta_{DCF}^2 L_2} + \frac{n_{eq-Ra2}}{G_{Ra1}} + \frac{n_{eq-Edf}}{G_{Ra1}^2} \right) \frac{\eta_{DCF} L_{DCF}}{G_{Ra1}} \exp (-\alpha_s L_1) L_{eff,Ra1} + \frac{\eta_{DCF} L_{DCF}}{G_{Ra1}} \exp (-\alpha_s L_1) L_{eff,Ra2} \right] \quad (16)
\]

\[
K_{al} = \int_{\text{length}} \gamma(z) P(z) \, dz = \gamma_{Ra1} P_s L_{eff,Ra1} + G_{Ra1} \exp (-\alpha_s L_1) L_{eff,Ra2} + \gamma_{DCF} P_s L_{eff,DCF} \exp (-\alpha_{DCF} L_{DCF}) G_{DCF} \quad (17)
\]

where suffixes Ra1 and Ra2 represent the RA#1 and RA#2 respectively. \( G_{tot}^{Ra} = G_{Ra1} \times G_{Ra2} \) is the total Raman on-off gain in the HFA, \( L = L_1 + L_2 \) is the total transmission fiber length, \( L_1 \) and \( L_2 \) are the transmission fiber lengths of the RA#1 and RA#2 respectively, and \( G(z, \zeta) \) represents the Raman amplification between the point \( z \) and \( \zeta \) in the transmission fiber.

In the optimization process of the hybrid dual-stage Raman/EDF amplifier, three more parameters are introduced: \( K_3 = G_{Ra1,Ab} / G_{tot,Ab} \) (representing the ratio of the RA#1 gain to the total Raman gain in the HFA), \( L_{fr} = L_3 / L \) (representing the ratio of the transmission fiber length of the RA#1 to the total transmission fiber length) and \( fr_p = P_{fr} / P_{pot} \) (representing the ratio of the forward pump power to the total pump power in RA#2). The optimal configuration is found by varying \( K_1, K_2, K_3, L_{fr} \) and \( fr_p \) until the OSNR is maximized.

In this analysis, we make use of the same parameter set given in Sect. 3. The maximum OSNR obtained is 46.65 dB at \( K_1, K_2, K_3, L_{fr} \) and \( fr_p \) equal to 0.25, 0.75, 0.15, 0.5 and 1, respectively. The maximum OSNR is 0.55 dB higher when compared with the optimal configuration of the single-stage HFA. Figure 5 shows the contour plot of the OSNR surface in the \( (K_1, K_2) \) where \( K_3, L_{fr} \) and \( fr_p \) are set as 0.15, 0.5, and 1, respectively. The OSNR drops dramatically when \( G_{tot}^{Ra} \) is larger than 50% of \( G_{tot} \) (top right hand corner of Fig. 5). This is due to the fact that DRB noise is the dominant noise source at high gain Raman amplifier. These results also show that although this configuration gives the highest OSNR, it is not the best configuration for getting high overall OSNR.

Figure 6 shows the contour plot of the OSNR surface in the \( (K_3, L_{fr}) \) where \( K_1, K_2 \) and \( fr_p \) are set as 0.25, 0.75,
and 1, respectively. The total Raman on-off gain is set at 4.97 dB, since the Raman gain is so small, the variation in $K_3$ and $L_{fr}$ brings a maximum difference of 0.8 dB in the OSNR. Therefore, the dual-stage Raman amplifier does not contribute much for improving the OSNR.

Since a bi-directional pumped Raman amplifier can reduce DRB noise under high gain condition [15], [16], the optimization process of the HFA was done again by keeping $f_{rp}$ at 0.5. The maximum OSNR obtained in the simulation is 46.6 dB at $K_1$, $K_2$, $K_3$ and $L_{fr}$, equal to 0.3, 0.75, 0.15 and 0.4, respectively, and it is plotted in Fig. 7 and Fig. 8. By comparing Fig. 7 with Fig. 5, the OSNR in the high Raman gain region has a significant improvement, the maximum improvement is approximately 7 dB.

However, Fig. 8 shows that the dual-stage Raman amplifier still does not contribute much in improving the OSNR. As $K_3$ and $L_{fr}$ vary, the difference in the OSNR is less than 0.9 dB. It is because the total Raman gain (5.96 dB) is too small.

In order to fully utilize the advantages of the dual-stage Raman amplifier, the total Raman gain should be set at a high gain value during the optimization process. For instance, if a wide-band HFA system has a maximum Raman gain ratio (ratio of Raman gain to total gain) of 0.81, then $K_1$ and $K_2$ should be set to a value which their multiple is equal to 0.81 during the optimization process.

Figure 9 shows the contour plot of the OSNR surface in the $(K_3, L_{fr})$ plan where $K_1$, $K_2$ and $f_{rp}$ are set as 0.9, 0.9 and 0.5, respectively. The maximum OSNR of 45.46 dB is achieved at $K_3 = 0.35$ and $L_{fr} = 0.95$.

Figure 10 shows the contour plot of the OSNR surface in the $(K_1, K_2)$ where $K_3$, $L_{fr}$ and $f_{rp}$ are set as 0.35, 0.95 and 0.5, respectively. When compare with Fig. 5 and Fig. 7, no much difference in OSNR value can be seen in

![Fig. 7](image7.png) Contour plot of the OSNR surface in the $(K_1, K_2)$ where $K_3$, $L_{fr}$ and $f_{rp}$ are set as 0.15, 0.4, and 0.5, respectively. The maximum OSNR has an input signal power of 12.58 dBm.

![Fig. 8](image8.png) Contour plot of the OSNR surface in the $(K_3, L_{fr})$ where $K_1$, $K_2$ and $f_{rp}$ are set as 0.3, 0.75, and 0.5, respectively.

![Fig. 9](image9.png) Contour plot of the OSNR surface in the $(K_3, L_{fr})$ where $K_1$, $K_2$ and $f_{rp}$ are set as 0.9, 0.9, and 0.5, respectively.

![Fig. 10](image10.png) Contour plot of the OSNR surface in the $(K_1, K_2)$ where $K_3$, $L_{fr}$ and $f_{rp}$ are set as 0.35, 0.95, and 0.5, respectively. The maximum OSNR has an input signal power of 11.62 dBm.
the low gain region. However, in the high gain region, the OSNR value shows an optimal improvement around 8 dB and 3 dB, respectively. The variation in OSNR from low to high Raman gain is less than 4 dB. Therefore, for this example configuration, optimal design of a hybrid dual-stage Raman/EDF amplifiers with a maximum Raman gain ratio of 0.81 is achieved at settings of $K_3$, $L_{fr}$ and $fr_p$ at 0.35, 0.95 and 0.5, respectively.

When comparing the results in Figs. 4 and 10, although the maximum OSNR value does not have a significant improvement, the OSNR value in the high Raman gain region shows an improvement close to 2 dB. This result clearly shows that a properly designed dual-stage Raman amplifier in HFAs can achieve a higher OSNR value at high Raman gain than a single-stage Raman amplifier and the variation in the OSNR can be reduced when Raman gain is varied within operational limits.

5. Conclusion

In this paper, a detailed model of a hybrid dual-stage Raman/erbium-doped fiber (EDF) amplifier (HFA) was presented. This model took into account the impact of double Rayleigh backscattering (DRB) noise, amplified spontaneous emission (ASE) noise and Kerr-nonlinearity induced impairments in the amplification process. Using this model, we presented a comprehensive analysis of the operation of hybrid dual-stage Raman/EDF amplifiers under above impairments. We showed that under fixed total gain conditions for the amplifier module, high Raman gain causes the introduction of increased DRB noise to the amplified signals whereas low Raman gain causes the introduction of high ASE noise power through EDF amplifier. Therefore, we found that a balance between the Raman amplifier gain and EDF amplifier gain is required for optimal operation.

For the example, the single stage RA system considered in our analysis, this optimal was achieved at $(K_1, K_2) = (0.2, 0.7)$ where the Raman on-off gain was set at 3.71 dB and an optical signal to noise ratio (OSNR) of 46.09 dB was achieved. When symmetric bi-directional pumped raman amplifier (RA) was used instead of backward pumped RA, the OSNR increased to 46.1 dB and the optimal point shifted to (0.25, 0.75).

We have also presented an optimization process for dual-stage Raman/EDF amplifier. We showed that by setting the total Raman gain to the required maximum value during the optimization process, we could obtain a configuration where the amplifier performance is most efficient. For example, the hybrid dual-stage Raman/EDF amplifier system considered in our analysis, we found a maximum Raman gain ratio of 0.81 with an optimal configuration at $K_3$, $L_{fr}$ and $fr_p$ equal to 0.35, 0.95 and 0.5, respectively. These results clearly show that using a hybrid dual-state Raman/EDF amplifier could achieve a higher OSNR than a single-stage Raman/EDF amplifier and must be considered as a serious contender in amplifying arena for the next generation optical networks.

References

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