Analysis of Distributed Raman Amplification in the S-band over a 100 km Fiber Span

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***Abstract*— The S-band is the next generation transmission window for dense wavelength division multiplexed systems. Distributed Raman amplification in the S band is specially challenging in optical communication systems deploying standard optical fibers. The pump wavelengths are located around the water peak wavelength for Raman amplification in the S-band region. The strong absorption around this wavelength region requires a higher pump power value to attain a given amount of on-off gain. Additionally, the effective noise figure of the distributed Raman amplifiers increases with pump absorption. The feasibility of a 70nm optical bandwidth Raman distributed amplification over 100km is numerically demonstrated using a True Wave Reach Low Water Peak optical fiber in the S-band. The reliability of the analysis lies in experimental Raman gain data, specially measured for S-band operation, used as input parameter in the numerical simulations. Additionally, the separation of the different processes to spectral gain shape in the analysis, such as pump-signal and pump-pump interactions, allows a straightforward determination of pump wavelengths and powers levels to cover the entire S band with minimum gain ripple. The analysis indicates the feasibility of a 15dB on/off gain with a gain ripple smaller than 2dB over 100km fiber span throughout the S band with the use of four pump lasers with power levels ranging from tenths to hundreds of miliwatts.**

***Index Terms*—** distributed Raman amplification, S-band, Low water peak fibers.

I. INTRODUCTION

Optical amplifiers are key devices to support DWDM transmission over long-haul optical fiber systems. The various optical amplifier technologies for the existing C (1530-1570 nm) and L (1570-1610 nm) bands are well established, among them Doped and Raman Fiber Amplifiers [1].

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Further increase in transmission capacity can only be achieved by either increasing spectral efficiency within the existing bands and/or extending system operation to other bands. Advances in fiber fabrication techniques, which pushed the low-loss transmission window of silica fibers down to wavelengths around the water-peak absorption turn the short wavelength side of the C-band, more precisely the S (1490-1530 nm) and S^+ (1460-1490 nm) bands [2,3,4], the next natural wavelength range to extend actual fiber systems operation.

In such context, Distributed Raman amplification is a well established approach to improve signal quality in long-haul, high-capacity fiber transmission systems [3,5]. It consists in coupling properly located pump lasers to the fiber span, turning the passive fiber into a distributed amplifier. By distributing the gain in the span, instead of deploying discrete amplifiers between the transmission links, allows the transmission of DWDM signals practically without loss while producing improved optical signal to noise ratio (OSNR).

In spite of several benefits provided by Distributed Raman amplifiers in the S-band, it also offers some challenges. As example, there are the pump wavelengths for S-band Raman amplification lying around the water-peak absorption wavelength region. For standard single mode fiber the attenuation value in this region is around 1dB/km. Such high attenuation value makes Distributed amplification very inefficient. Therefore, fibers with reduced water-peak absorption are the best candidate to employ Distributed amplification in the S-band. This is the case of TrueWave® Reach - Low Water Peak optical fiber that has low attenuation around water-peak wavelength, which typical value is smaller than 0.35dB/km at 1383 nm if compared to 1dB/km of a standard single-mode fiber.

Distributed Raman amplification over 100km of TrueWave® Reach - Low Water Peak optical fiber span operating in the S band is numerically evaluated in this report. The reliability of the numerical simulations lies in the experimental Raman gain efficiency data specially measured, by authors' request, for the TrueWave® Reach - Low Water Peak optical fiber for S band operation. In Section II, the experimental Raman gain efficiency data for a 1420nm wavelength pump is reported. In addition, S-band operation requires multi-wavelength pump lasers sources. Therefore, Raman gain efficiency for additional pump wavelengths is also estimated taking into account its inverse dependence with pump and signal wavelengths, in Section II. Usually Raman gain efficiency wavelength dependence is disregarded in DRA´s C-band operation. Nonetheless its impact in the S-band gives around 15% variation in Raman gain efficiency to the shorter signal wavelength (1460nm) with respect to longer signal wavelength (1530nm), which translates in a 4dB gain difference. In Section III, the implementation of the standard DRA coupled nonlinear equation is reported [3,6], where the different processes contributions to gain spectral shape, such as pump-signal, pump-pump, and signal-signal interactions are separated. This separation allows straightforward determination of pump wavelengths and power levels to achieve 70nm gain over 100km fiber span with minimum gain ripple, rather than using complex and time consuming optimization computational algorithms [9]. This straightforward

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adjustment in pump powers levels indicates the feasibility of a 15dB on/off gain with a ripple smaller than 2dB in a 70 nm range using four pump lasers with power levels ranging from tenths to hundreds of miliwatts. Finally, we conclude in Section IV.

II. S BAND RAMAN GAIN EFFICIENCY

OFS Fitel Denmark provided the measured Raman gain efficiency for TrueWave® Reach - Low Water Peak optical fiber curve for the S-band to pump wavelength (λ_p) equal to 1420 nm, which is shown in *Fig.*1.

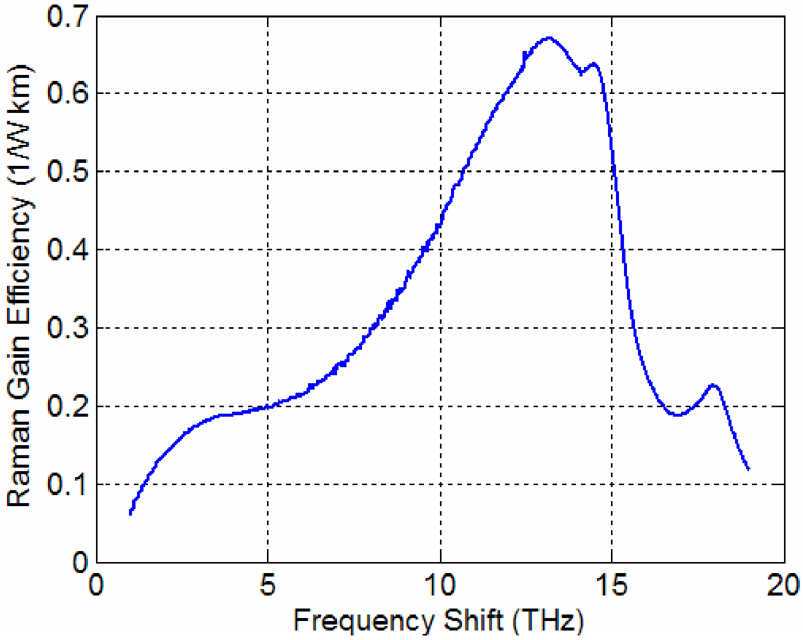

Fig. 1. Measured Raman gain efficiency curve (λ_p=1420nm).

The S-band True Wave® Reach – Low Water Peak (LWP) optical fiber has a maximum Raman gain efficiency of $0.6721W^{-1}km^{-1}$ for a signal frequency 13.2 THz down-shifted relative to a 1420 nm pump wavelength. In terms of wavelength, the maximum Raman gain efficiency is 94.86 nm up-shifted from pump wavelength, more precisely, at 1514.9 nm signal wavelength.

Additional pump wavelengths have to be considered in order to obtain Raman gain over the entire S-band, i.e., from 1460 nm to 1530 nm. Considering eight signal channels spaced by 10 nm within the S-band, the respective pump wavelength considered is 13.2THz up-shifted from signal frequency. The pump/signal pair wavelengths are 1371.7/1460.0nm, 1380.5/1470.0nm, 1389.3/1480.0nm, 1398.1/1490.0nm, 1406.9/1500.0nm, 1415.7/1510.0nm, 1424.5/1520.0nm, and 1433.3/1530.0nm and their respective separation are 88.3nm, 89.4nm, 90.6nm, 91.8nm, 93.0nm, 94.2nm, 95.4nm and 96.7nm.

The Raman efficiency curve for the eight pumps is estimated from the measured Raman gain efficiency using the relation [6,7]:

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$$C_R^E\left(\lambda_p,\lambda_s\right)=\frac{\lambda_i}{\lambda_s}\frac{A_{eff}\left(\lambda_i\right)}{A_{eff}\left(\lambda_s\right)}C_R^M\left(\lambda_k,\lambda_i\right). \quad (1)$$

In equation (1), $C_R^M\left(\lambda_k,\lambda_i\right)$ and $A_{eff}\left(\lambda_i\right)$ are the measured Raman gain efficiency and effective area at pump and signal wavelength λ_k and λ_i respectively, meanwhile $C_R^E\left(\lambda_p,\lambda_s\right)$ and $A_{eff}\left(\lambda_s\right)$ are the estimated Raman gain efficiency and effective area at the desired pump and signal wavelength λ_p and λ_s respectively.

The Raman gain efficiency curves are estimated for the pump wavelengths at 1371.7nm, 1380.5nm, 1389.3nm, 1398.1nm, 1406.9nm, 1415.7nm, 1424.5nm and 1433.3nm using measured effective area values which range from 12 to 16μm^2 for wavelengths in the S-band and the measured Raman gain efficiency data for λ_p equal to 1420nm. The estimated Raman gain efficiency curves are illustrated in *Fig*.2. The shorter wavelength signals have higher Raman gain efficiencies, the difference among Raman gain peak efficiency (depicted in *Fig*.2) of the shortest and longest wavelength signals are of 0.1W^{-1}km^{-1}. Besides the contribution from paired pump to signal gain, the unpaired ones also transfer part of its energy to the other signals (although not so efficiently). Table I summarizes Raman gain efficiency values to all possible pump-signal coupling contributions.

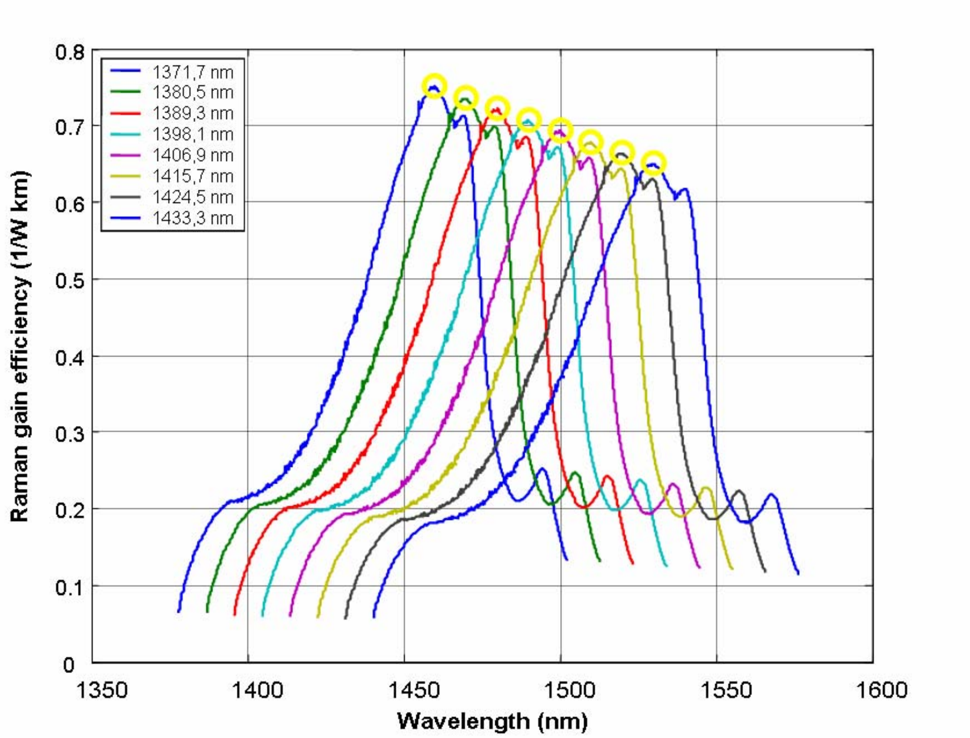

Fig.2. Raman gain curves estimated from measured data for wavelength pumps at 1371.7nm, 1380.5nm, 1389.3nm, 1398.1nm, 1406.9nm, 1415.7nm, 1424.5nm and 1433.3nm.

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TABLE I: RAMAN GAIN EFFICIENCY FOR ALL PUMP-SIGNAL COUPLING COMBINATIONS

		Pump wavelengths (nm)							
		1371.7	**1380.5**	**1389.3**	**1398.1**	**1406.9**	**1415.7**	**1424.5**	**1433.3**
Signal wavelengths (nm)	**1460**	0.751	0.649	0.514	0.386	0.288	0.229	0.195	0.181
	1470	0.705	0.736	0.638	0.507	0.375	0.290	0.230	0.194
	1480	0.271	0.694	0.721	0.627	0.500	0.373	0.284	0.224
	1490	0.220	0.271	0.682	0.707	0.616	0.486	0.374	0.282
	1500	0.163	0.213	0.272	0.669	0.693	0.605	0.482	0.370
	1510	-----	0.169	0.207	0.271	0.656	0.678	0.593	0.473
	1520	-----	-----	0.176	0.201	0.272	0.643	0.664	0.581
	1530	-----	-----	------	0.182	0.195	0.272	0.631	0.650

In wide band amplification, such as 70nm, the power transfer from shorter to longer wavelength pumps is a relevant process [8]. In *Fig.*3 each pump Raman gain efficiency curve is illustrated along with the corresponding spectral pump location. The correspondence is depicted labeling the arrows and corresponding curves as (a), (b), …, (h).

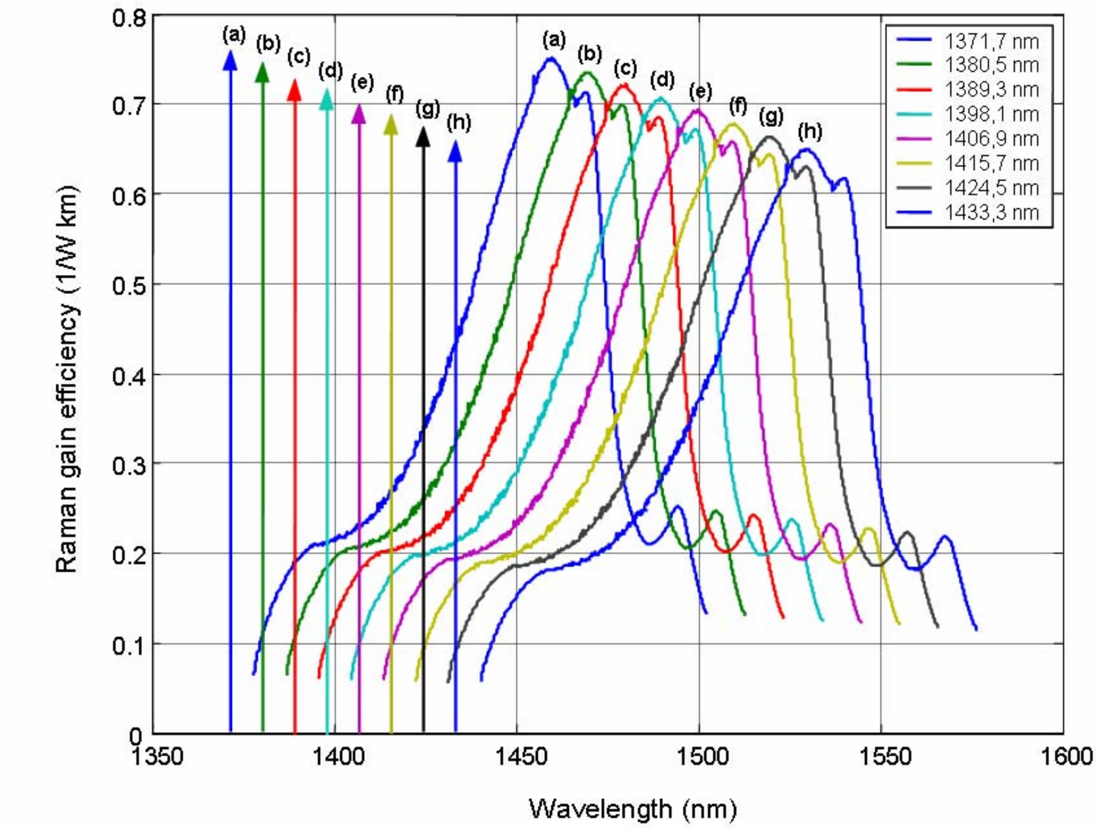

Fig. 3. Raman gain efficiency curve for eight pump wavelengths 1371.7nm, 1380.5nm, 1389.3nm, 1398.1nm, 1406.9nm, 1415.7nm, 1424.5nm and 1433.3nm. The arrows set each pump wavelength location.

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The intersection between arrows and curves gives the specific pump-pump Raman gain efficiency coupling. For example, the interception between arrow (b) and curve (a) corresponds to an efficiency of $0.1W^{-1}km^{-1}$. This is the efficiency with which the 1371.7 nm pump wavelength scatters the 1380.5nm pump wavelength. The number of interception increases with pump wavelength. Table II summarizes the Raman gain efficiency values for all pump-pump interactions possibilities.

TABLE II: RAMAN GAIN EFFICIENCY FOR PUMP-PUMP COUPLING

		Scattered Pump Wavelengths (nm)							
		1371.7	**1380.5**	**1389.3**	**1398.1**	**1406.9**	**1415.7**	**1424.5**	**1433.3**
Scattered Pump Wavelengths (nm)	**1371.7**	----	0.109	0.190	0.211	0.229	0.268	0.338	0.430
	1380.5	----	----	0.105	0.185	0.206	0.224	0.259	0.323
	1389.3	----	----	----	0.102	0.179	0.202	0.221	0.249
	1398.1	----	----	----	----	0.098	0.173	0.196	0.213
	1406.9	----	----	----	----	----	0.095	0.169	0.194
	1415.7	----	----	----	----	----	----	0.091	0.165
	1424.5	----	----	----	----	----	----	----	0.088
	1433.3	----	----	----	----	----	----	----	----

III. RAMAN AMPLIFICATION NUMERICAL EVALUATION

The 100 km fiber span distributed Raman gain is simulated using the well established coupled nonlinear equations for the signals and pumps average powers. Parameters, which allow the separation of the different processes contributing to Raman gain, are introduced in the equations. Details are discussed in the Appendix. The analysis carried here accounts for Raman interaction between pump-signals and pump-pump. Fiber attenuation values for pump and signal wavelengths were also provided by OFS Fitel Denmark, and are also listed in the Appendix.

A. Pump-signal interaction

We focus on on-off gain analysis over the entire S-band. The on-off gain is defined as an increase of signal power at the amplifier output when the pumps are turned on. A simple and straightforward start consists in considering eight backward propagating pumps evenly spaced, more precisely at 1371.7nm, 1380.5nm, 1389.3nm, 1398.1nm, 1406.9nm, 1415.7nm, 1424.5nm, and 1433.3nm wavelengths.

The on-off gain in the S-band in the absence of unpaired pump-signal coupling (only the diagonal terms in Table I) and pump-pump interaction is illustrated in *Fig*. 4. All pump wavelengths have equal power varying from 0mW to 150mW. The longer wavelength signals are 1dB above the shorter wavelength signals for the 150mW pump power. This feature is a consequence of pump absorption being smaller for longer pump wavelengths (see Table IV in the Appendix for details). Therefore for the same pump power they reach a higher gain. The equations (A.1) to (A.3) in the Appendix have an algebraic solution in the limit described here if the pump depletion terms are disregarded. The algebraic results (symbols in *Fig*.4) are in good agreement with numerical ones (solid lines in *Fig*.4).

Even in the absence of pump-pump interactions, once the contributions of all pump-signal couplings

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(paired and unpaired ones) are accounted in the analysis the on-off gain spectral shape changes completely, as depicted in *Fig*.5. Overall, the on-off gain is almost 30dB above the results in *Fig*.4. Nonetheless, the shorter wavelength signals are around 10dB above the longer wavelength signals. This characteristic is due to the higher Raman gain efficiency for shorter signal wavelength, as discussed in *Fig*.2.

B. Pump-pump interaction

Power transfer from short wavelength pumps to longer wavelength pumps (pump-pump interaction) induces higher and more efficient scattering in the longer wavelengths in the S-band. The effect of pump-pump interaction in the analysis is illustrated in *Fig*.6, where the backward pump power along the span is calculated, illustrating the longer wavelength pump amplification.

The on-off spectral shape changes considerably with the addition of pump-pump interaction to the analysis as well. The on-off gain is illustrated in *Fig*.7 (solid lines) in combination with the on-off gain in the absence of pump-pump interactions (dashed lines). As expected the pump-pump interactions favors the longer wavelengths. For example, for all pumps power equals to 150mW the on-off gain at the end of the band are above 15dB if compared to the ones in the beginning of the band.

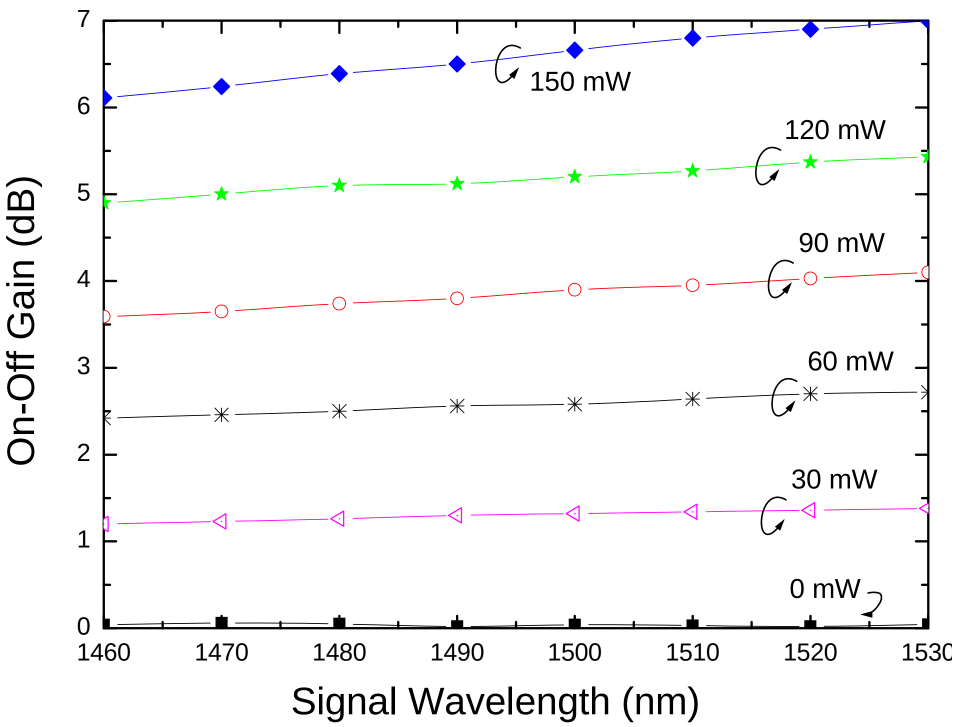

Fig. 4. On-off gain for 100km distributed Raman amplification in the S-band. The pump wavelengths are centered at 1371.7nm, 1380.5nm, 1389.3nm, 1398.1nm, 1406.9nm, 1415.7nm, 1424.5nm, and 1433.3nm and are propagating backward with respect to the signals. The pumps have equal powers of 0mW, 30mW, 60mW, 90mW, 120mW and 150mW. Only paired pump/signal contributions where accounted.

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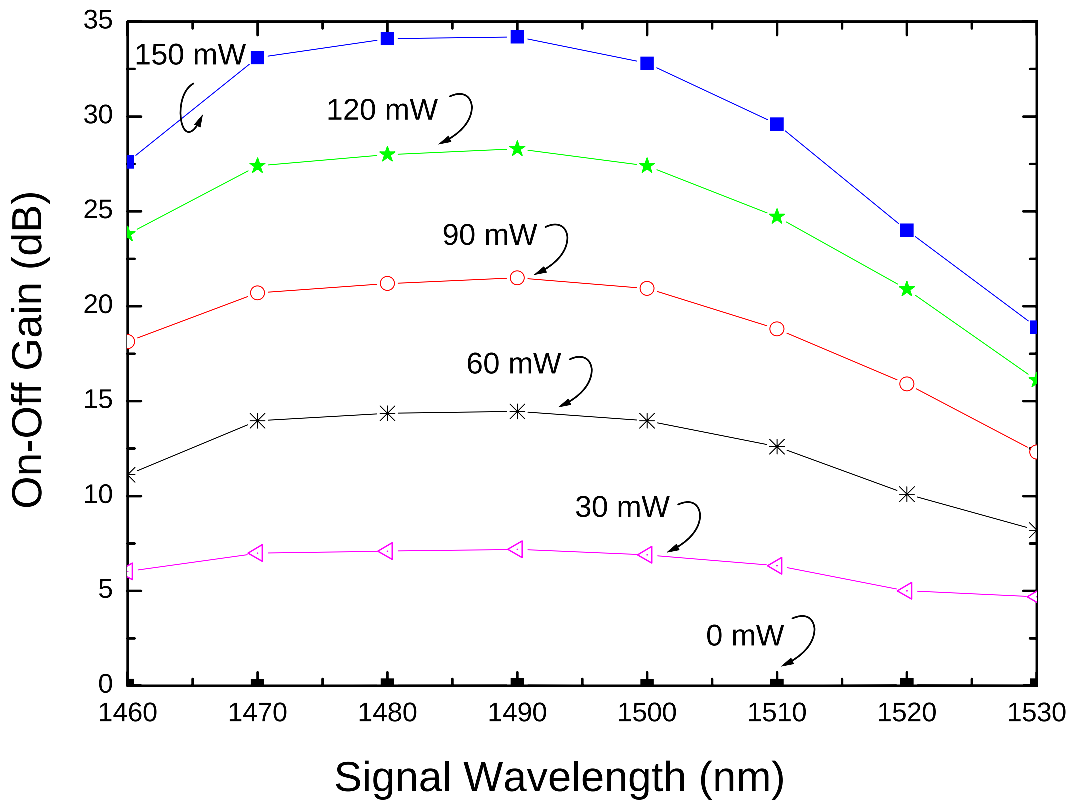

Fig.5. On-off gain for 100km distributed Raman amplification in the S-band. The pump wavelengths are centered at 1371.7nm, 1380.5nm, 1389.3nm, 1398.1nm, 1406.9nm, 1415.7nm, 1424.5nm, and 1433.3nm and are propagating backward with respect to the signals. The pumps have equal powers of 0mW, 30mW, 60mW, 90mW, 120mW and 150mW.

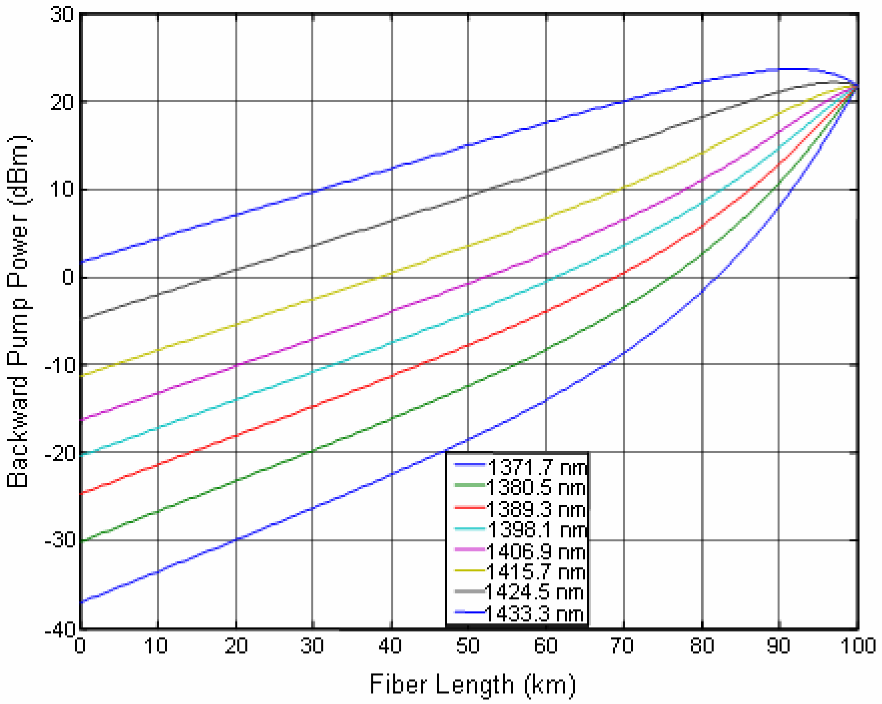

Fig.6. Backward pump power along the 100km span. All pumps are launched at span end with 150mW.

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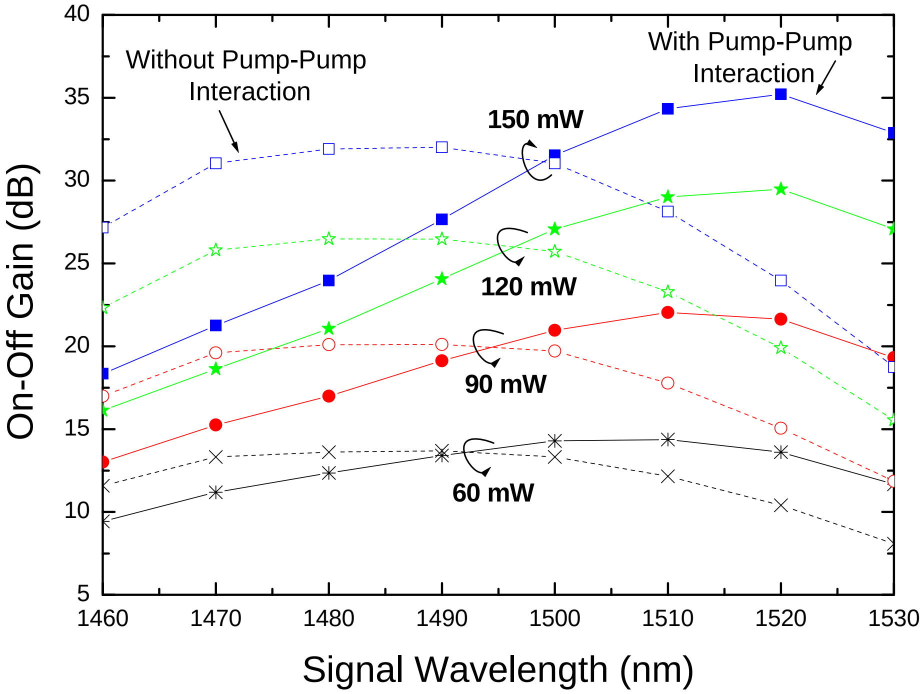

Fig. 7. On-off gain for S-band distributed Raman amplification for backward pump propagation. The pump wavelengths are centered at 1371.7nm, 1380.5nm, 1389.3nm, 1398.1nm, 1406.9nm, 1415.7nm, 1424.5nm, and 1433.3nm. The dashed lines assigns specific pump powers in the absence of pump-pump interaction and solid line assigns specific pump powers in the presence of pump-pump interaction.

Pump-signal coupling favors gain to the shorter wavelength signals while pump-pump signal coupling favors the longer wavelength signals. Pump-pump interaction starts to dominate over pump-signal interaction for pump powers higher than 120mW, as depicted in *Fig*.7. This feature evidences the compromise between pump powers level, on-off gain and gain ripple tolerance. If one wants to keep the on-off gain as high as 35dB, a flatter behavior over the S-band is achieved reducing the longer wavelength pump power while enhancing the shorter wavelength pump power. Such a 35 dB on-off gain is achieved using 8 pumps. If no adjustment in the relative pump powers is considered, the amplifier operation is restricted to half the S band bandwidth, more precisely between 1500 nm and 1530 nm.

For practical purposes, it is interesting to reduce the number of pump sources. For instance, four pump coupling at wavelengths 1371.7nm, 1389.3nm, 1406.9nm, and 1424.5nm reduces the on-off gain level from 35dB to 20dB for pump powers equals to 150mW. Adjustment of the relative pump powers enable attaining a flatter on-off gain with a ripple better than 2 dB in the whole S band, as illustrated in *Fig*.8. The adjustment consisted in a 75% increase in the 1371.7nm wavelength pump power (from 150mW to 262.5mW), and a 70% reduction in the 1406.9nm wavelength pump power (from 150mW to 45mW). This simple and straightforward adjustment, suggested in the graphical analysis, allows compensating the 15dB on-off gain variation.

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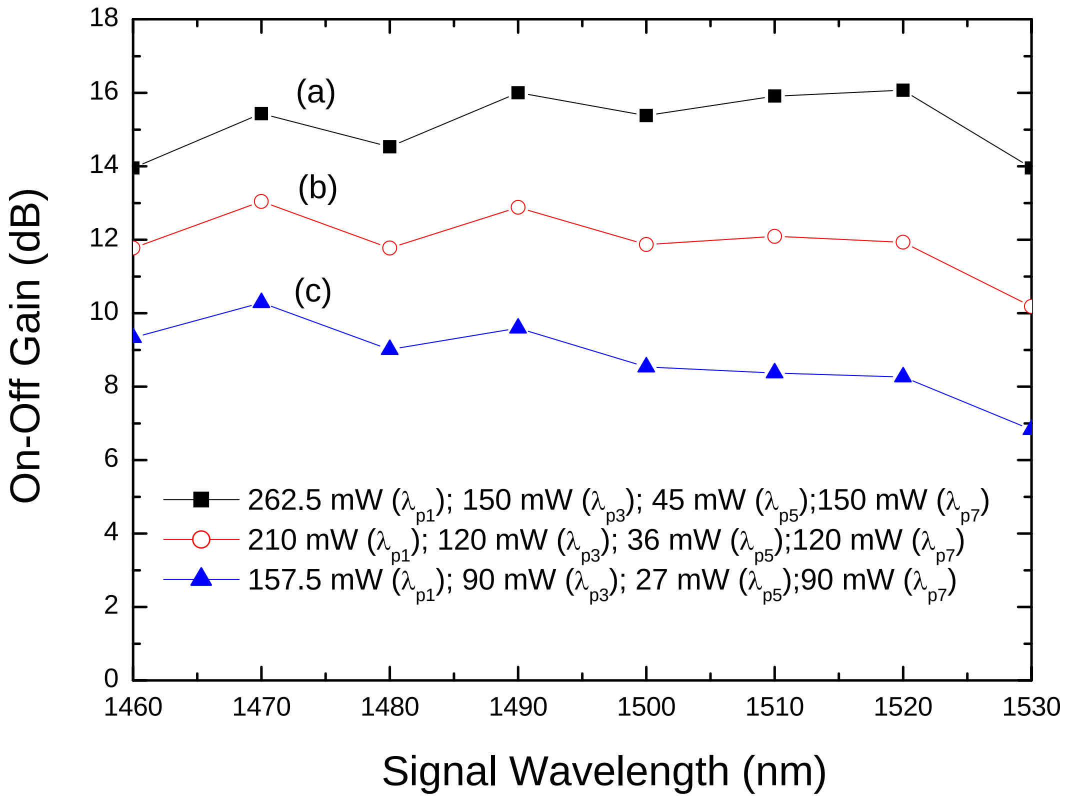

Fig. 8. On-off gain for S-band distributed Raman amplification for backward pump propagation. Four pump at wavelengths of λ_{p1}=1371.7 nm, λ_{p3}= 1389.3 nm, λ_{p5}=1406.9 nm and λ_{p7}=1424.5 nm are backward propagating with respect to the signals. The power in λ_{p1} and λ_{p5} are respectively increased in 75% and reduced in 70% with respect to an equal power for all pumps of (a) 150mW; (b) 120mW; (c) 90mW.

IV. CONCLUSIONS

Distributed Raman amplification performance in the S band was numerically investigated deploying a TrueWave® Reach - Low Water Peak optical fiber over a 100km fiber span. The Raman gain efficiency of the TrueWave® Reach - Low Water Peak optical fiber was experimentally characterized by OFS Fitel for a pump wavelength of 1420nm. Further adjustment of the experimental data allowed to account for Raman gain dependence with pump and signal wavelengths. Additionally, the standard nonlinear coupled DRA equations were numerically implement, using the carefully treated experimental data as input and separating the different process which contribute to DRA spectral shape. This procedure allowed a direct comparison between DRA spectrum in the presence and absence of pump-pump interactions, and consequently a straightforward adjustment in pump power level in order to minimize DRA´s gain ripple. The analysis indicated the feasibility of a 15dB on/off gain with a gain ripple smaller than 2dB over 100km fiber span throughout the S band with the use of four pump lasers with power levels ranging from tenths to hundreds of miliwatts.

APPENDIX

The gain profile of broad band distributed Raman amplifiers taking into account the interactions of pump-to-pump, signal-to-signal and pump-to-signal, as well as amplified spontaneous emission and attenuation can be simulated by the coupled nonlinear equations [3,6]

$$\frac{dP_{s,i}}{dz} = -\alpha_{s,i} P_{s,i} + \sum_{\substack{j \\ (\lambda_i > \lambda_j)}} \varepsilon^3_{i,j} C^R_{i,j} \left(P^f_{p,j} + P^b_{p,j} \right) P_{s,i} \tag{A.1}$$

$$\frac{dP^f_{p,j}}{dz} = -\alpha_{p,j} P^f_{P,j} - \sum_{\substack{i \\ (\lambda_i > \lambda_j)}} \varepsilon^3_{i,j} \left(\frac{\nu_{p,j}}{\nu_{s,i}} C^R_{j,i} P_{s,i} \right) P^f_{p,j} + \left[\sum_{\substack{k \\ (\lambda_k < \lambda_j)}} C^R_{j,k} P^f_{p,k} - \sum_{\substack{k \\ (\lambda_k > \lambda_j)}} \frac{\nu_{p,k}}{\nu_{p,j}} C^R_{k,j} P^f_{p,k} \right] \varepsilon^2_{k,j} P^f_{p,j} \tag{A.2}$$

$$\frac{dP^b_{p,j}}{dz} = +\alpha_{p,j} P^b_{p,j} + \sum_{\substack{i \\ (\lambda_i > \lambda_j)}} \varepsilon^3_{i,j} \left(\frac{\nu_{p,j}}{\nu_{s,i}} C^R_{j,i} P_{s,i} \right) P^b_{p,j} - \left[\sum_{\substack{k \\ (\lambda_k < \lambda_j)}} C^R_{j,k} P^b_{p,k} - \sum_{\substack{k \\ (\lambda_k > \lambda_j)}} \frac{\nu_{p,k}}{\nu_{p,j}} C^R_{k,j} P^b_{p,k} \right] \varepsilon^2_{k,j} P^b_{p,j} \tag{A.3}$$

In equations (A.1) - (A.3) the sub-index $i = 1,...N_s^{Max}$ identifies a specific signal wavelength within the S-band, ranging from 1460 nm to 1530 nm ($i = 1$ corresponding to $\lambda_{s,1} = 1460nm$ and $i = N_s^{Max}$ corresponding to $\lambda_{s,N_s^{Max}} = 1530nm$). $P_{s,i}$ and $\alpha_{s,i}$ are the signal average power and attenuation at signal wavelength $\lambda_{s,i}$ (with respective frequency $\nu_{s,i}$), respectively. The sub-index $j = 1,..., N_p^{Max}$ identifies a specific pump wavelength ranging from 1371.1nm to 1433.3nm ($j = 1$ corresponding to $\lambda_{p,1} = 1371.7nm$ and $i = N_s^{Max}$ corresponding to $\lambda_{p,N_s^{Max}} = 1433.3nm$). $P^x_{p,j}$ and $\alpha_{p,j}$ are the pump average power and attenuation at pump wavelength $\lambda_{p,j}$ (with respective frequency $\nu_{p,j}$), where $x = f, b$ denotes forward and backward propagation. The sub-index k identifies a shorter wavelength pump which transfers power to a longer wavelength pump. C^R_{mn} is the Raman gain efficiency from a signal of wavelength λ_n to a signal of wavelength λ_m.

The first and second terms in equations (A.1) denote signal attenuation and Raman gain contribution from a pump wavelength λ_j to a wavelength signal λ_i signal, respectively. The first term in equation (A.2) denotes forward pump attenuation, and Raman depletion by Stokes lights a signal λ_i to a pump wavelength λ_j. It is presented in the second term of equation (A.2) the coupling between a pump of wavelength λ_k to a pump wavelength λ_j. The backward pump equation is equal to $\left(-dP^f_{p,j} / dz\right)$.

Additional parameters, $\varepsilon^2_{k,j}$ and $\varepsilon^3_{i,j}$, are inserted in the set of equations (A.1)-(A.3). Their aim is to provide flexibility to the analysis separating the different process to the amplification spectral shape profile. For example if $\varepsilon^3_{i,j} = 1$ and $i = j$, and $\varepsilon^3_{i,j} = 0$ for $i \neq j$ the analysis accounts only for coupling between pump/signal pairs. Setting $\varepsilon^3_{i,j} = 1$ for $i \neq j$ accounts for coupling between paired and unpaired pump, and $\varepsilon^2_{k,j} = 1$ for $k \neq j$ accounts for pump-pump interaction and $\varepsilon^2_{k,j} = 0$ for $k \neq j$ disregards it.

TABLE IV. ATTENUATIONS α_p AND α_s AT PUMP AND SIGNAL WAVELENGTHS λ_p AND λ_s RESPECTIVELY

λ_p(nm)	**α_p(dB/km)**	**λ_s(nm)**	**α_s(dB/km)**
1371.7	0.34416	1460	0.24131
1380.5	0.33250	1470	0.23417
1389.3	0.31988	1480	0.22817
1398.1	0.30688	1490	0.22332
1406.9	0.29410	1500	0.21900
1415.7	0.28213	1510	0.21473
1424.5	0.27154	1520	0.21053
1433.3	0.26273	1530	0.20657

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