Noise Figure and Pump Reflection Power in SMF-Reach Optical Fibre for Raman Amplification

G. M. Isoe, E. K. Rotich, D. K. Boiyo, R. R. G. Gamatham, A.W. R. Leitch and T. B. Gibbon
Optical Fibre Research Unit, Physics Dept.,
Nelson Mandela Metropolitan University, South Africa

K. M. Muguro and D. W. Waswa,
Optical Fibre and Laser Research Group, Physics Dept.,
University of Eldoret, Kenya

***Abstract*— We investigate both experimentally and by simulation the Noise Figure (NF) and pump reflection power of a Distributed Fibre Raman Amplifier (DFRA) as a function of pump power and fibre length, at different pump configurations. A DFRA of lengths 25 km and 50 km has been experimentally designed using Single Mode Reach Fibre (SMF-Reach) with an attenuation of 0.20 dB/km. Two pumping techniques namely Co-pumping and counter pumping have been used. It was found that the increase in fibre length, lead to increase in the NF irrespective of the pumping technique used. A NF of -2.2 dB and -1.9 dB was achieved experimentally for Co- and Counter pumping schemes respectively, for a 25 km fibre at 23 dB pump power. For a 50 km fibre, a NF of -1.8 dB and -0.7 dB was obtained for the two pump configurations respectively, under the same pump power. Pump reflection power varied inversely with gain and directly with fibre length. This work recommends Co-pumping technique in signal transmission due to its low NF and pump reflection power.**

Keywords*— *Raman Fibre amplifier, Noise Figure, Optical Signal to Noise Ratio

I. INTRODUCTION

Among the advanced technologies attained in recent years is the introduction of Fibre Raman Amplifiers (FRAs) which have enabled the optical signals in optical fibres to be amplified directly in high bit rate systems even beyond Terabits. This has been achieved by increasing the bit rate per channel, and also increasing the number of optical channels per fibre, so as to support high speed data transmissions in modern optical communication systems.

FRAs presents very attractive features both in long haul signal transmissions, as well as passive optical networks (PONs) for metropolitan applications compared with other optical amplification solutions [2-5]. The ability to adjust the gain profile and improved Noise Figure are among these attractive features [6, 7]. The other outstanding characteristic of Raman amplification is that it can occur in any fibre. However there are fibres that are designed and optimized for Raman amplification. Optical amplification is the main source of intrinsic noise in optical fibres which arises as a result of Amplified Spontaneous Emission (ASE). Optical noise has a direct and multiple implications on the performance of optical communication systems, because it degrades the Optical Signal to Noise Ratio (OSNR) [8]. It also induces timing jitter and frequency fluctuations of the amplified optical signal [9-12].

We are grateful for Research Funding and support from: Telkom, Dartcom, Ingoma, CISCO, DST, CSIR, NLC, NRF, THRIP, ALC and scholarship funding from SKA/NRF.

It is therefore significant to analyze the noise performance and pump reflections in modern fibres in order to gain deep understanding of their onset in amplified optical communication systems.

Some resent research on noise figure contribution to optical noise in Distributed Fibre Raman Amplifier has so far been done [13, 14, and 15]. However traditional fibres were used which were limited by higher signal dispersion and impurities levels. In our approach, we use newly fabricated modern fibres which are of improved qualities and of low polarization mode dispersion (PMD) [16]. We investigate and characterize the noise performance as well as analyze pump reflections in these fibres when used as gain mediums during Raman amplification. We have also demonstrated a noise figure suppression technique through Co-pumping technique in fibre Raman amplification. This work will contribute to current understanding of the onset of optical noise and pump reflection power in these modern fibres thus providing a major step towards improvement of the overall performance efficiency of modern optical fibre communication systems.

II. OPTICAL NOISE SOURCES IN RAMAN FIBRE AMPLIFIERS

There are various optical noise sources in Raman fibre amplifiers. The first primary source of optical noise is the Amplified Spontaneous Emission noise (ASE). Optical noise due to ASE is an inherent noise and occurs in all optical amplifiers. Any amplified light signal experiences an optical noise normally generated in the amplification process. The ASE noise is as a consequence of spontaneous Raman scattering (SRS) during the process of signal amplification. As a result of its random phases, the ASE is generated in all directions within an optical fibre, and also exists in the amplifier bandwidth.

The ASE noise effect on the performance of a FRA can be described in terms of two parameters namely Optical Signal to Noise Ratio (OSNR) and Noise Figure (NF). The parameter OSNR is defined as the ratio of the signal optical power to the power of the ASE with respect to a given reference bandwidth centered about the signal wavelength [17].The reference bandwidth is often referenced to 0.1 nm when measured using an optical spectrum analyzer (OSA). The NF is the ratio of the signal to noise ratio (SNR) at the input of an amplifier to that at the output of an amplifier. ASE noise increases the NF as well as degrading the OSNR by simply adding a wider band of background noise around the signal wavelength hence affecting the general performance of the optical communication system [18]. The system's NF can be improved by filtering out the

978-1-4799-7498-6/15/$31.00 ©2015 IEEE

ASE at the amplifier output by placing an optical filter just before the receiver.

Another source of optical noise is the Relative Intensity Noise (RIN), which originates from the short upper-state lifetime of Raman amplification. Because stimulated Raman scattering is a non-resonant phenomenon, it is therefore inherently fast occurring over sub-pico-second time scales [19]. As a result of this, pump power fluctuations can be transferred to signals as noise. In FRAs, the pump and signal interacts over a time scale that is relatively prolonged because they propagate along over several kilometers with the transmission span. This therefore results to an averaging effect that generally increases the chances of pump noise transfer to the signals [20]. This entire phenomenon can be described in the frequency domain as a transfer of relative intensity noise (RIN) from a pump to a signal.

Double Rayleigh scattering (DRS) is also another primary source of noise in fibre Raman amplifiers. DRS corresponds to two scattering events, one on a backward direction while the other on a forward direction. It comes about as a result of un-uniformity in the microscopic glass composition within the transmission fibre. DRS is an impairment most responsible for Multipath Interference (MPI) noise. MPI noise can severely affect the transmission performance of a long-haul Raman based transmission system. With sufficient Raman gain in the transmission span and minimum ASE noise, MPI presents the next important limit to long distance transmissions when implementing Raman amplification.

There are three basic pumping techniques popularly used in Raman amplification in optical fibres. The pump and the signal can co-propagate, thus the method is called forward or Co-pumping. When the signal propagates through the fibre in the opposite direction to the pump, the technique is called counter or backward pumping. There is also bidirectional pumping where two pumps are employed simultaneously at opposite ends of the transmission fibre during amplification. The noise performance of RFA relies greatly on the pumping technique applied. However, each of these pumping configurations has its own advantages which make them equally competitive. The choice of a particular scheme to adapt can only be determined using performance criteria of a particular RFA design [21].

For instance, the Co- and counter pumping techniques are different in terms of noise performances. This originates from the different amount of averaging time that occurs when a signal wavelength propagating along the fibre overlaps with the pump wavelength. As for counter pumping, the signal and pump counter propagate through each other and the averaging time greatly reduces the impact of pump fluctuations above a few kilohertz thus minimizing the pump to signal noise transfer [22]. As a rough estimate, a remarkable drop in RIN noise transfer occurs for any pump fluctuations with a period larger than the propagation time through a given transmission span. However, for the case of co-pumping, the pump and signal only counter propagate through each other if there is a walk-off caused mainly by Chromatic Dispersion (CD). Therefore, averaging time will only result into RIN noise transfer at much higher wavelengths [23].

One of the techniques mainly used to minimize destructive coupling is through utilization of counter pumping technique. When the pump and signal are made to counter propagate each other, an effect is brought about where the effective upper-state lifetime equals to the transit time through the transmission span hence reducing the RIN noise transfer significantly.

III. THEORY

The noise figure (NF) of an optical amplifier is the ratio of the OSNR of the input signal to the OSNR of the output signal. It is also a measure of how much an amplifier can degrades a signal. In any Raman amplified system; the equivalent noise figure (NF_{eq}) represents the NF of an amplifier placed at the receiver end of the transmission span [24]. For a distributed fibre Raman amplifier, the evolution of the spectral density, NS of the optical noise at the signal wavelength is expressed as [25].

$$\frac{dN_s}{dZ} = -\alpha_s\left[N_s - \frac{hv_s}{2}\right] + G_R P_p\left[N_s + \frac{hv_s}{2}\right], \qquad (1)$$

where G_R and α_s are the fibre Raman gain efficiency and fibre attenuation coefficient respectively.

$$N_s = G\frac{hv_s}{2} + (G-1)\frac{hv_s}{2} + 2\alpha_s G D_{\text{inv}}\frac{hv_s}{2}, \qquad (2)$$

Where $D_{\text{inv}} = \int_0^l \left(\frac{1}{G(z)}\right) dz, \qquad (3)$

D_{inv} (vacuum fluctuation), is a type of input noise reference which under signal amplification contributes to an output noise, in addition to intrinsic noise generated in the process of amplification [26]. The input noise can also be defined as the vacuum fluctuation. If we consider a white Gaussian noise in the limited optical measurement bandwidth (0.1nm), the NF will be defined as:

$$NF = \frac{N_s}{G\frac{hv_s}{2}}, \quad NF = 1 + \frac{G-1}{G} + 2\alpha_s D_{\text{inv}}$$

IV. EXPERIMENTAL SETUP

Fig.1 shows a schematic configuration of a distributed Raman Fibre Amplifier (RFA) used in the experimental measurement. A -10 dBm signal source transmitted at 1550 nm wavelength was used. The signal was obtained from an externally modulated distributed feedback laser (DFB) whose maximum power rating is 12 dBm. A Raman pump operating at a wavelength of 1450 nm and with a variable output power of up to 23 dBm was used in the experiment. This ensured maximum amplification of the signal which in RFA occurs when the pump-signal detuning is 100 nm. A variable optical attenuator was connected to the signal source to vary the amount of power getting to the receiver so as to attain the optimum signal power required. An isolator was then connected to the pump and signal laser sources to maintain the signal in one direction thus protecting the laser sources from the counter-propagating laser light.

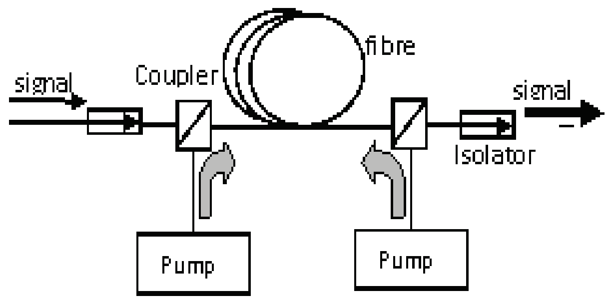

Fig. 1: Schematic of an optical communication system employing Raman amplification.

The states of polarization (SOPs) of the signal and the pump were controlled using polarization controllers (PCs). Consequently, the signal source and the pump were coupled into the fibre using a filter based Wavelength Division Multiplexer (WDM) as the input coupler. Both were then propagated in a 25 km SMF-reach after which the pump wavelength was filtered out and the output signal analyzed. The same procedure was repeated for a 50 km fibre. The signal power at the fibre output was measured using a GFHP-B power meter. The noise power at the output was analyzed separately using the optical spectrum analyzer (OSA) and the resultant NF measured on the scope. Both forward and backward pumping techniques were applied and the results analyzed.

V. RESULTS AND DISCUSSION

Fig. 2 shows experimental and simulation measurements of the effect of pump power on pump reflection for co- and counter pumping scheme using a 25 km SMF-Reach fibre.

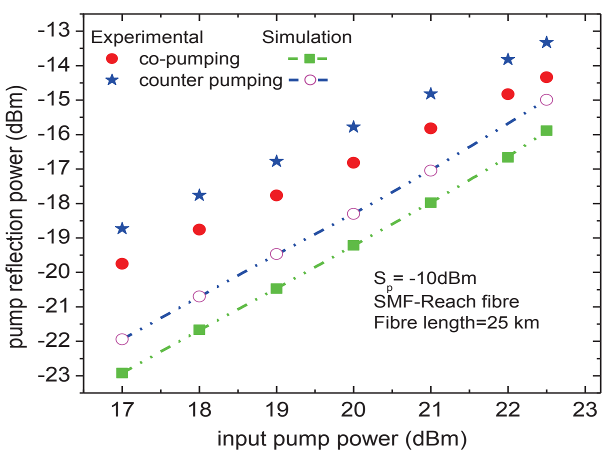

Fig. 2: Experimental and simulation effects of pump power on pump reflection for a 25 km SMF-Reach fibre at co- and counter pumping scheme.

From Fig. 2, the amount of pump reflection power was dictated by the pumping scheme used. This was attributed by the fact that in co-pumping, the signal power and the pump power both travelled in the same direction. This in turn ensured that there was more pump penetration into the signal thus more pump energy was transferred to the signal, leading to higher gains due to proper utilization of the pump. Very minimal pump power was therefore left unutilized in this pumping scheme thus the pump reflection power was very minimal. For the case of counter pumping, the signal and the pump both propagated in a direction opposite to each other. This meant that there was minimal pump to signal power transfer thus much of the pump power was left highly unutilized. This unutilized pump power was then reflected back and detected as pump reflection power thus accounting for the higher pump reflection power recorded in the counter pumping scheme.

Fig. 3(a) shows the effect of pump power on pump reflection for 25 km and 50 km SMF-Reach fibre lengths for the co- pumping scheme. It was noted that an increase in fibre length lead to a decrease in pump reflection power for the case of co-pumping scheme. This was because as the fibre length was increased, the contact time between the pump and the signal also increased, thus more of the pump power was utilized and less was reflected back.

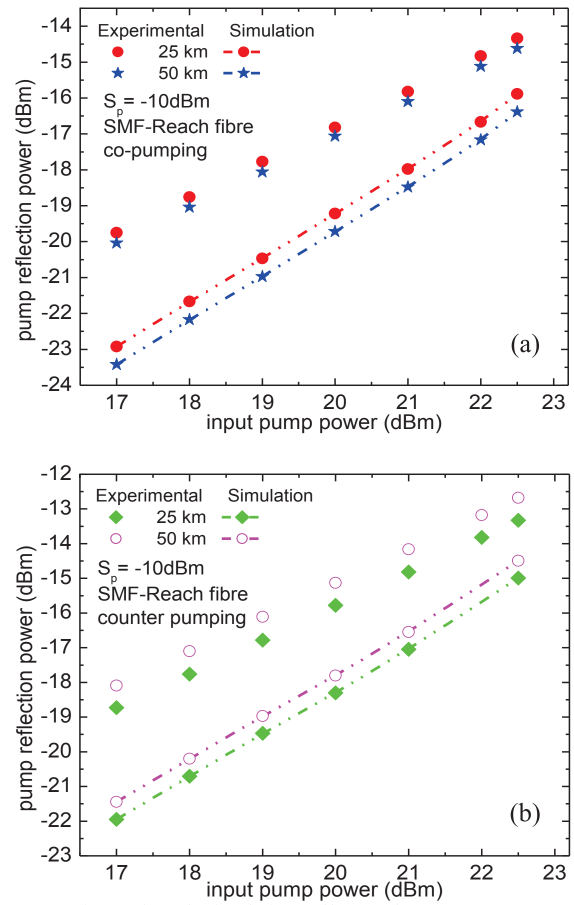

Fig. 3: Experimental and simulation effects of pump power on pump reflection for (a) 25 km and 50 km SMF-Reach fibre at co- pumping, (b) 25 km and 50 km SMF-Reach fibre at counter pumping.

For the case of counter pumping, an increase in fibre length lead to a further increase in pump reflection power as shown in Fig. 3(b). As the fibre length was increased, the pump and the signal had to cover a longer distance hence weakening further due to attenuations within the fibre. The ratio between the pump and the signal also reduced significantly as the pump approached a relatively stronger signal from the opposite end of the fibre. This in turn limited the pump to signal power transfer by a greater factor. The unutilized pump power was then reflected back and detected as pump reflection power.

Experimental results in Fig. 3 (a) and (b) gave a lower pump reflection compared to the simulation results in both pumping schemes because of the passive components used in the experimental work like connectors, isolators and WDM filters. These components reflected much of the power, which was not the case in the simulation.

Fig. 4 shows the effective NF of co- and counter pumping schemes for 25 km fibre length.

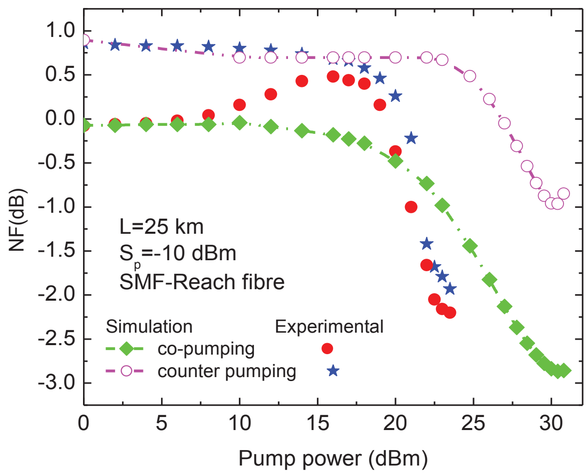

Fig. 4: NF variations with pump power for co-pumping and counter pumping schemes, experimental and simulation results.

From fig.4, the NF for co-pumping increased gradually with increase in pump power up to 17 dBm. This was because these pump powers were still low to induce remarkable SRS hence a continuous increase in pump power lead to more pump to signal relative intensity noise (RIN) transfer to the signal. RIN was more dominant in co- pumping than in counter pumping at pump powers of up to 17 dBm. As the pump power was increased beyond 17 dBm, the NF reduced with increase in pump power in the two pump techniques. The pump power over this region (beyond 17 dBm) was now strong enough to boost the signal power thus accounting for the continuous decrease in the NF.

Co-pumping gave a better NF performance than counter pumping because for the case of co-pumping, both the pump power and the signal power were propagated in the same direction. This ensured that the pump was well utilized by the signal thus more pump power was transferred to the signal hence higher amplification levels were achieved. Also the ratio between the pump power and the signal power was maintained almost at the same level throughout the transmission span. For the case of counter pumping, the signal was propagated in a direction counter to the pump. This limited the pump to signal power transfer thus leaving much of the pump power unutilized hence accounting for the higher NF attained in this pumping scheme.

Theoretical results were obtained through simulation of a 25 km fibre and having similar characteristics as the one used in the experiment. In this case, the NF reduced gently in the two pumping schemes for pump powers of up to 23 dBm because theoretical simulation assumed that the pump power over this range was not powerful enough to compensate for losses in the signal as it propagated through the fibre. This meant that the signal power remained at low power over this region thus resulting to a higher NF over this power region. As pump power was increased above 20 dBm the NF gradually reduced in both co- and counter pumping schemes.

Experimental measurement gave a higher NF compared to that obtained in the simulation. This was due to noise generation from passive components like connectors, isolators and WDM couplers which to some extent are polarization dependent loss devices. These components which are normally incorporated in any fibre optic system also add up losses to the signal during experimental measurements.

Fig. 5 shows the effective NF variation with pump power for co- pumping at different fibre lengths.

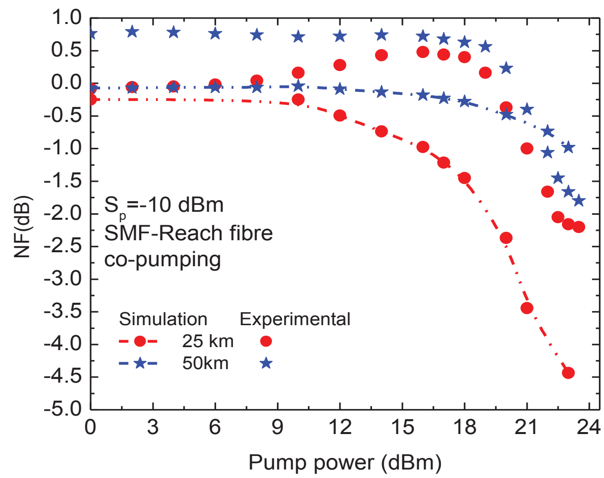

Fig. 5: Effective Noise Figure (dB) as a function of pump power at different fibre lengths, experimental and simulation measurement.

The NF increased slightly for pump powers of up to 17 dBm. This was due to RIN noise transfer to the signal which was dominant at these low pumping powers. As the pump power was increased beyond 17 dBm, the NF decreased greatly in both fibre lengths because these pump powers was strong enough to amplify the signal thus compensating signal for losses within the transmission fibre.

A 50 km fibre gave a higher NF than a 25 km Fibre because as the fibre length is increased, the contact time between the pump and the signal also increased thus more RIN noise transfer from the pump to the signal especially at lower pump powers. This increase in fibre length also leads to an increase in gain which in turn led to increased ASE noise generation in the process of attaining this higher gain.

Simulation results in Fig. 5 were obtained with fibres of same lengths and characteristics. These results show a similar trend to the experimental results. In this case, NF was lower because there were no losses at the connections as it was with experimental setup.

VI. CONCLUSION

Optical noise effects in optical fibres and optical communication components have been a subject of great interest and concern in the implementation of optical fibre technology. In this work, the effects of optical noise in distributed RFA designed using SMF-Reach modern optical fibres were investigated. SRS which is a scattering phenomenon have been used to convert the fibre into an amplifying medium so that the signal strength can be restored and maintained within the fibre for long haul transmissions. The effect of Fibre lengths and pump powers, NF and pump reflection have been studied at different pumping schemes. From our results, the NF increased with increase in fibre length. This increase was more significant in counter pumping than in Co-pumping. The ASE noise was also minimal in the co- pumping thus accounting for the lower NF recorded in this pumping scheme. This makes Co-pumping superior in noise performance compared with the counter pumping. We recommend this pumping configuration in long haul signal transmission.

REFERENCES

[1] Agrawal G. P., *Fibre Optical Communications Systems*, 3rd Edition, John Willey& Sons, inc., 2002.

[2] Mori T., Masuda H., Shikano K., and Shimizu M., “Ultra-wide-band tellurite-based fibre Raman amplifier,” Journal of Lightwave Technology, pp. 1300-1306, (2003).

[3] Monroy T., Kjær R., Öhman F., Yvind K., Jeppesen P., “Distributed fibre Raman amplification in long reach PON bidirectional access links,” Optical Fibre Technology, Elsevier, vol. 14, pp. 41-44, (2008).

[4] Islam M., “Raman amplifiers for telecommunications,” *IEEE J. Sel. To.Quantum Electron.*, vol. 8, no. 3, pp. 548–559, May/Jun. (2002).

[5] Clifford H., and Agrawal G. P., *Raman Amplification in Fibre Optical Communication Systems*, Elsevier Ac. Press, USA, 2005.

[6] Thyagarajan K., and Ghatak A., “Some Important nonlinear effects in optical fibres Guided Wave Optical Components and Devices: Basics, Technology, and Applications,” Bishnu P. Pal, Ac. Press, pp. 91-121, (2006).

[7] Bindal, A., and Surinder S., "Gain saturation as a function of pump parameters in fiber Raman amplifiers.," Proceedings of the 11th WSEAS international conference on Electronics, Hardware, Wireless and Optical Communications, and proceedings of the 11th WSEAS international conference on Signal Processing, Robotics and Automation, and proceedings of the 4th WSEAS international conference on Nanotechnology. World Scientific and Engineering Academy and Society (WSEAS), 2012.

[8] Fludger C. R. S., Handerek V., and Mears R. J., “Fundamental noise limits in broadband Raman amplifiers,” in Proc. Optical Fibre Communications Conf., (2001).

[9] Gordon J. P., and Haus H. A., “Random walk of coherently amplified solutions in optical fibre transmission,” *Opt. Lett.*, vol. 11, no. 10, p. 665, (1986).

[10] Pinto A. N., Agrawal G. P., and da Rocha J. R. F., “Effect of soliton interaction on timing jitter in communication systems,” *J. Lightw. Technol.*, vol. 16, no. 4, pp. 515–519, (1998).

[11] Pinto A. N., da Rocha J. R. F., Lin Q. and Agrawal G. P., “Optical versus electrical dispersion compensation: Role of timing jitter,” *J. Lightw. Technol.*, vol. 24, no. 1, p. 387, (2006).

[12] Pinto A. N., and Agrawal G. P., “Nonlinear interaction between signal and noise in optical amplifiers,” *J. Lightw. Technol.*, vol. 26, no. 13, pp. 1847–1853, (2008).

[13] Wang, Haitong, and Jian Jin. "Analysis of the noise figure of Raman fiber amplifier." Mechatronic Science, Electric Engineering and Computer (MEC), 2011 International Conference on. IEEE, 2011.

[14] Wang, S. H., Lixin Xu, and P. K. A. Wai. "Optimal noise figure for Raman-assisted fiber optical amplifiers." Opto-Electronics and Communications Conference, 2008 and the 2008 Australian Conference on Optical Fibre Technology. OECC/ACOFT 2008. Joint conference of the. IEEE, 2008.

[15] André P. S., Pinto A. N., Teixeira A.L.J., Neto B., Stevan S., Donato S., da Rocha F., Micaela B., Pinto J. L., Meire F., Ana R., and Facão M., “new challenges in Raman Amplification for Fiber Communication Systems,” Optical Fibers Research Advances, Edition: 1, Chapter: 2, Publisher: Nova Science Publishers, Inc., pp.51-81.

[16] Azami N., “Characterization of polarization-dependent gain in Raman fiber amplifier,” Optics Communications, vol. 230, pp. 181-184 (2004).

[17] Dimitropoulos D., Solli R. D., Claps R., Boyraz O., and Jalali B., “Noise Figure of Silicon Raman Amplifiers,” Journal of Lightwave technology, Vol. 26, No. 7, (2008).

[18] Jordanova L.T. and Topchiev V.I., “Improvement of the Optical Channel Noise Characteristics Using Distributed Raman Amplifiers”, ICEST Conference, pp. 20-23 (2008).

[19] Yariv A., *Optical Electronics in Modern Communications*, 5th ed. Oxford University Press, New York, Chap. 16, 1997.

[20] Fludger C. R. S., Handerek V., and Mears R. J., “Pump to signal RIN transfer in Raman fibre amplifiers,” J. Lightwave Technol., vol. 19, pp. 1140–1148, (2001).

[21] Kim C. H., Son E.S., Cho H-S., Han Y-G, Ju Han Lee and S. Bae Lee, “Experimental study on the effect of codirectional Raman gain on system’s performance,” Opt. Express, vol. 15, pp. 6146-6151 (2007).

[22] Ohki Y., Hayamizu N., Shimizu H., Irino S., Yoshida J., Tsukiji N., and Namiki S., “Increase of relative intensity noise after fibre transmission in co-propagating Raman pump lasers,” in Proc. Optical Amplifiers and Their Applications, (2002).

[23] Fludger C. R. S., Handerek V., and Mears R. J., “Fundamental noise limits in broadband Raman amplifiers,” in Proc. Optical Fibre Communications Conf., (2001).

[24] Bromage J., “Raman Amplification for Fibre Communications Systems,” journal of lightwave technology, vol. 22, no. 1, (2004).

[25] Bristiel B., Shifeng J., Gallion P., Pincemin E., “New model of noise figure and RIN transfer in fibre Raman amplifiers”, Photonics Technology Letters, IEEE Volume 18, Issue 8, pp.980 - 982, April 2006.

[26] Haus H. A., “The noise figure of optical amplifiers,” IEEE Photon. Technol. Lett., vol. 10, no. 11, pp. 1602–1604, Nov., (1998).