OPTIMIZATION OF THE UNREPEATERD LINKS WITH REMOTE AMPLIFIERS

S.B.Papernyi

serguei.papernyi@mpbc.ca

MPB Communications Inc, 147 Hymus Blvd, Pointe Claire, Quebec, H9R 1E9, Canada

Abstract: A new transmission link configuration with remote Er post- and pre-amplifiers where pump power is shared between a pair of fibers carrying traffic in opposite directions is proposed. Experimental verification of the principle was successfully carried out for single-channel 2.5GHz transmission. More than 4 dB budget improvement was achieved for a total link loss >90dB using only one third-order cascaded Raman pump source per transmission fiber.

1 INTRODUCTION

The longest unrepeatered links utilize a remotely pumped Er post-amplifier (Tx ROPA), located ~30-70 km from the transmit terminal, in addition to a remote pre-amplifier (Rx ROPA), typically positioned ~100-140 km from the receive terminal. Pumping of the ROPAs can be accomplished either by directly launching high power at ~1480 nm (first-order pumping) or through the generation of 1480-nm pump power inside the transmission fiber (or dedicated pump-delivery fibers) via high-order cascaded Raman processes [1-4]. The Raman effect in the fiber limits the delivered to a ROPA power. At certain Raman gain the “useful” power at 1480 nm is transferred into high order Stokes components and at even higher pump powers due to the Rayleigh scattering excess noise at signal band is generated in the form of random pulsing. It was found that Raman gain in commonly used transmission fibers should not exceed ~35-40 dB. This limit translates into the launch power limit for the first order 1480-nm pumping at 1-1.5W depending on fiber type. For the third order cascaded pumping the primary pump power at 1276-nm is limited at ~3.5-4.5W.

A Rx ROPA can be pumped through the transmission fiber and/or dedicated delivery fibers. On the other hand, in the case of Tx ROPAs Raman interactions between high-power pump and co-propagating signal preclude transmission fiber usage for the pump delivery because at any reasonable launch signal power amplified signal very quickly “overshoots” nonlinear limit at the same time limiting the transmitted pump power.

As a result, all systems with a Tx ROPA have to date utilized one or two pump sources with each connected to a dedicated pump-delivery fiber. Although utilizing two dedicated fibers and Tx ROPA pump sources allows additional optical budget increase of ~ 9-12 dB, the improvement comes at the expense of a substantial increase in system cost and complexity [3,4].

In the Table 1 are shown optical budget improvements for different remote amplifier configurations as compared to the link without remote amplifiers.

Link configuration	Pumps	Add fibers	Link Loss	Improvement
Booster + Preamplifier	**0**	0	66	0
1st order Raman Amplifier	**1**	0	73	7
3rd order Raman Amplifier	**1**	0	75	9
Rx ROPA – 3rd order Raman pump	**1**	0	86	20
Tx+Rx ROPA sharing – 3rd order Raman pump	***1***	***0***	***90***	***24***
Tx+Rx ROPA – 3rd order Raman pump	**2**	1	97	31
Tx+Rx ROPA – 3rd order Raman pump	**3**	2	99	33

Table 1

Link losses are shown for the error free transmission of the single 2.5Ghz signal with Forward Error correction (FEC). Of course absolute budget value depends on the fiber type and signal modulation format but the improvement is practically independent on these factors.

In this paper we propose and demonstrate new Tx +Rx link architecture that eliminates co-propagating Raman interactions and does not require dedicated fibers and pump sources for pump delivery to a Tx ROPA. This approach can potentially provide up to 5 dB of budget improvement compared to the best achievable with a Rx ROPA alone, but does not require dedicated delivery fibers nor dedicated Tx ROPA pump sources. The concept applies to the most common type of link, one consisting of a pair of fibers carrying traffic in opposite directions, and is based on the idea of power sharing between the two fibers. In [5], the application of a power-sharing concept for providing distributed Raman amplification was theoretically explored. However, the principle was not experimentally investigated and, in fact, our detailed calculations have shown that using power sharing for Raman amplification cannot provide any significant budget improvement. On the other hand, we will show that when applied to the remote pumping of Er amplifiers, it provides a cost-effective means of realizing substantial budget increases.

2 BUDGET IMPROVEMENT CALCULATIONS

The power-sharing concept is illustrated in the experimental set-up shown in Figure1.

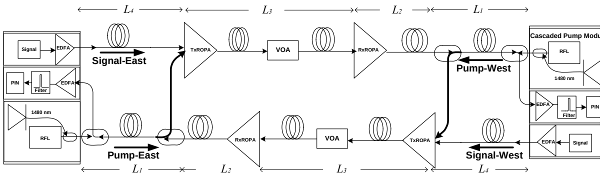

Figure 1: Transmission link layout

Part of the pump power travelling "East" towards a Rx ROPA (amplifying signals travelling "West") is split off at the location of a Tx ROPA in the fiber carrying data "East" and used for pumping this Tx ROPA. Thus, the "West-East" transmission fiber is used for pump delivery to the "East-West" Tx ROPA (and vice versa) and therefore, co-propagating Raman interactions are eliminated. The link consists of four fiber lengths where: L_1 is the distance from the pump source (receiver side) to a point where part of the pump power is split between fibers (S-point); L_2 - the distance from the S-point to the Rx ROPA; L_3 - the distance between the Tx and Rx ROPAs; and $L_4 = L_1$ - the distance from the transmitter to the Tx ROPA (i.e. the total link length $\boldsymbol{L} = L_1 + L_2 + L_3 + L_4$)

For the first-order pumping, maximal length $\boldsymbol{L}$ can be calculated starting from the following equation for the pump power delivered to the Rx ROPA:

$$P_{Rx} = [P_0 \times exp(- \alpha_p L_1) - P_{nl}/\eta] \times exp(- \alpha_p L_2) \quad (1)$$

where P_{Rx} is the delivered pump power required at the Rx ROPA for optimal gain and noise figure performance of the amplifier, α_p is the fiber loss at the pump wavelength and η is the efficiency of the Tx ROPA and P_0 is the maximal value of the pump power limited by Raman effect as it was mentioned above.

It is fair to assume that P_0, P_{Rx} and P_{nl} and so the distance L_3 should be constants for a particular fiber type and signal modulation format.

The link will have the longest length when $(2L_1 + L_2)$ reaches its maximal value consistent with the requirements that: 1) the pump power reaching the Tx ROPA be sufficient to ensure the signal output power is at the limit (P_{nl}) imposed by nonlinear effects and 2) the pump power reaching the Rx ROPA will provide optimal gain and noise figure performance of the amplifier.

Under these assumptions, the optimal location of the Tx ROPA (L_{1opt}) that provides the longest link can be derived from equation (1):

$$L_{1opt} = (1/\alpha_p) \times ln(\eta P_0 / 2 P_{nl}) \qquad (2)$$

From (1) and (2) we find that, for first-order pumping, the optimum split ratio is 50/50%. The maximum budget improvement (not accounting for any nonlinear penalties introduced by the Tx ROPA) compared to the best achievable with a Rx ROPA alone is given by:

$$\Delta \boldsymbol{B} = \alpha_s [2L_{1opt} + L_2 + L_3) - (L_{3R} + L_5)] = 10log(e) \times (\alpha_s/\alpha_p) \times [ln(\eta P_0 / 4P_{nl})] \qquad (3)$$

where α_s is the fiber loss at the signal wavelength and L_{3R} and L_5 are the optimal distances, for the case of no Tx ROPA, from the transmitter to the Rx ROPA and from the Rx ROPA to the receiver (pump laser). Under our assumptions, it is clear that $L_3 = L_{3R}$ and $L_5 = (1/\alpha_p) \times ln(P_0/P_{Rx})$.

Figure 2 illustrates the estimated budget improvement vs. the distance from the pump source to the S-point for both first- and third-order pumping for a realistic Tx ROPA efficiency of 65% and a fiber with parameters close to those of pure silica core fiber (i.e. $\boldsymbol{\alpha_s}$=0.17 dB/km and $\boldsymbol{\alpha_p}$=0.2 dB/km). For third-order pumping, it is not possible to calculate the budget improvement in a closed form and the curve shown in Figure 2 is the result of numerical modeling. The numerically calculated improvement was found to be ~2dB higher than that for the first-order pumping because the 1480-nm pump power achieves its maximum value ~25 km from the launch point and the "effective" 1480-nm launch power is ~2 dB higher [2,4].

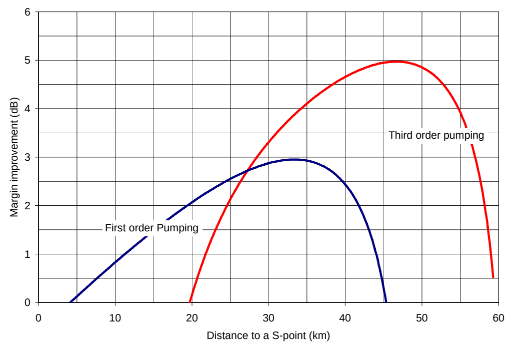

Figure 2: Calculated budget improvements for the First & Third – order ROPA Pumping

3 TRANSMISSION EXPERIMENT

A transmission experiment was carried out in Corning Vascade EX1000 fiber with average losses of 0.169 dB/km at 1552 nm and 0.195 dB/km at 1485 nm (these values include splice and connector losses averaged through the fiber length). A single 2.5GHz signal, appropriately dithered for stimulated Brillouin scattering suppression, was amplified in an Er-doped booster amplifier having a saturated output power up to 21 dBm. It was found that the nonlinear limit for the signal launch power P_{nl} was 20 dBm. A third-order cascaded Raman pump scheme [2,4] was used for ROPA pumping. The pump source consisted of a 1276-nm high-power Raman laser with a maximum output power of 4 W, plus a seed LD at 1485 nm with a power output up to 100 mW. Two fiber Bragg gratings, reflecting incoming Raman ASE at 1360 nm and 1427 nm back into the span were spliced between the Raman laser and the entrance of the transmission link to provide feedback for the build-up of the second-order Stokes powers out in the span.

Two tests were carried out with the setup shown in Figure 1. In the first test, the distance to the S-point (Tx ROPA) was 35.75 km, in the second it was increased to 50.75 km. The split ratio in the first case was 30/70% with 30% of the power used for pumping the Tx ROPA and 70% propagating on towards the Rx ROPA. In the second test, the split ratio was 60/40% with the 60% being used for Tx ROPA pumping. In order to keep the Rx ROPA pumping constant in both tests, the fiber length from the S-point to the Rx ROPA was changed from 89 km to 63 km. In both tests, the pump power delivered to each ROPA was the same: 135 mW for the Tx ROPA and 6.6 mW for the Rx ROPA. These values were found to be optimal and provided a Tx ROPA efficiency of 63% (including losses in WDMs and isolators) and a Rx ROPA gain of 18 dB and noise figure of 5.6 dB. A VOA located between the Tx and Rx ROPAs was used for changing the total link losses.

A direct comparison with the "Rx ROPA alone" configuration was made by simply taking out the Tx ROPA, reconnecting the link and appropriately adjusting the VOA settings. Of course, the losses in the pump-power WDM splitter were taken into account when calculating the total link budget.

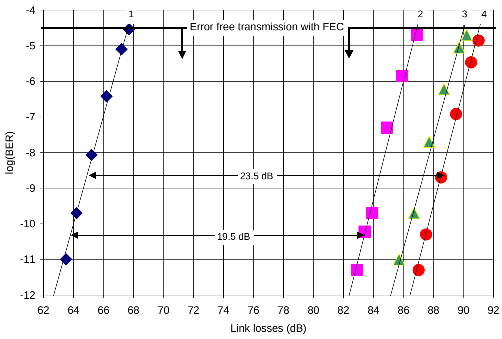

Figure 3: BER measurements vs. link losses. 1.-without ROPAs, 2. only Rx ROPA at optima position, 3&4.- with Tx ROPA placed at 35.75 and 50.75 km form the pump source.

As can be seen in Figure 3, the addition of the Tx ROPA and pump power sharing between the pair of fibers provides up to 4 dB of margin improvement for a total link loss of ~ 90 dB. The measured improvement values are approximately 1 dB smaller than predicted. This could be attributed to a nonlinear penalty caused by the Tx ROPA. In other words, the nonlinear limit of the Tx ROPA output power was found to be ~19.3 dBm as compared to the P_{nl} of 20 dBm at the booster output when the link did not include the Tx ROPA (though we do not have a clear explanation for this fact).

In conclusion, we have proposed and demonstrated a new link configuration that allows a budget increase > 4 dB with only one ROPA pump source per transmission fiber and no dedicated pump delivery fibers.

4 REFERENCES

[1] F.Boubal, J-P.Blondel, E.Brandon, L.Buet, V.Havard, L.Labrunie, P. Le Roux, "Recent unrepeatered WDM 10Gbit/s experiments in the range 300 km to 450 km," Suboptic2001, Kyoto, Paper P3.6.

[2] S.Papernyi, V.Karpov, W.Clements, "Third-Order Cascaded Raman Amplification," OFC2002, Anaheim, postdeadline paper FB4.

[3]. L.Labrunie, F.Boubal, P. Le Roux, E.Brandon, "500km WDM 12 x10 Gbit/s CRZ repeaterless transmission using second order remote amplification," Electronic Letters, Vol39, No 19, pp1394-1395, 2003.

[4] V.Karpov, S.Papernyi, V.Ivanov, W.Clements, T.Araki, Y.Koyano, "Cascaded pump delivery for remotely pumped Erbium doped amplifiers," Suboptic2004, Paper We.8.8.

[5] C.R.S Fludger, V.Handerek, N.Jolley, R.J.Mears, "Inline loopbacks for improved OSNR and reduced double Rayleigh Scattering in distributed Raman Amplifiers," OFC 2001, Baltimore, paper MI1-1.