More than 30 dB Budget Improvement in Unrepeatered 100 GHz Links

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Serguei Papernyi
MPB Communications

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Serguei Papernyi, Wallace Clements, Bernard Shum-Tim, MPB Communications Inc
e-mail:serguei.papernyi@mpbc.ca.

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

Abstract: A new communications link configuration is presented with co-located Tx and Rx ROPAs inserted in two fibers carrying traffic in opposite directions and sharing pump power from a single pump source. The methodology to be followed to optimize the placement of the joint ROPA enclosure is discussed and a link budget increase up to 32 dB is experimentally demonstrated for 100 G transmission with 3rd order cascaded ROPA pumping. This novel configuration makes it possible for essentially no additional cost to extend reach by ~10 dB compared to a link configuration with Rx ROPA alone.

1. Introduction

Subsea and terrestrial unrepeatered communications strive to achieve longer distances at higher bit rates. The most effective way to increase the link budget is to use Remote Optically Pumped Amplifiers (ROPA). A Rx ROPA alone pumped through the transmission fiber in the direction opposite to the signal propagation can provide an increase in link budget of more than 20 dB, see for example [1]. ROPA pumping by third-order cascaded Raman has been shown to allow the largest terminal to ROPA distance [2-5] and thus the longest reach increase. Adding a transmit ROPA (Tx ROPA) can provide an additional budget increase which depends on pumping scheme. The amount of power delivered to the ROPAs is limited mainly by the Raman gain. High Raman gain (G) leads to a loss of the desired 1480-nm pump power as it is converted to amplified noise around 1525 and 1600 nm and can ultimately lead to random lasing spike generation. A typical gain curve in the case of 3rd order pumping is shown in Figure 1. Gain should be kept smaller than G_{max}~35-40 dB depending on the fiber type and pumping method. In the signal band, high Raman gain and double Rayleigh scattering lead to a Multi-Pass Interference (MPI) penalty which places a limit on the gain in this region of ~ 28 dB.

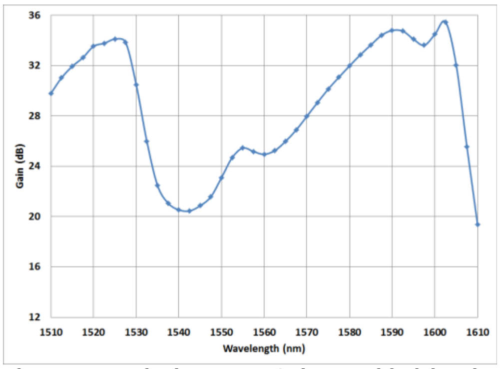

Figure 1. Typical Raman Gain provided by the 3rd order cascaded Raman ROPA pump

If a Tx ROPA is pumped through the transmission fiber, the delivered power is not only limited by these issues but also by pump-to-signal intensity noise transfer [6] and possible saturation effects. Of course, to overcome these limitations, it is possible to use large-mode-area fibers that reduce Raman gain and increase the signal nonlinear power limit. Also, significant increases in link budget can be achieved by using dedicated ROPA pump delivery fibers. Long link unrepeatered "hero" experiments, for example [3,7,8], have used all or a combination of these technologies as well as distributed co-propagating Raman amplification.

However, keeping CapEx and OpEx costs and system complexity in check is essential for practical deployment. Here, we introduce a Tx&Rx ROPA configuration based on a ROPA pump-sharing architecture [1, 9]. The idea of sharing pump power between fibers carrying traffic in opposite directions was first introduced in [10], and applied to distributed Raman amplifiers. In [1], it was shown that pump sharing between Tx and Rx ROPAs pumped by a single source launched from the receiving terminal can provide a significant improvement of the link budget. The idea of our present approach is to **optimize the position of a single**, common Tx&Rx ROPA enclosure (in contrast to [1]) and to share between the co-located ROPAs the power delivered by a single third-order ROPA pump, see Figure 2.

It will be shown that, compared to a link with a Rx ROPA alone, this configuration provides a substantial budget increase with essentially no increase in cost.

through the same fiber carrying the outgoing signals.

In [8], another pump sharing concept for "enhanced" co-located ROPAs was reported. In this scheme, separate multiplexed 14xx-nm laser diode modules pumped the Tx and Rx ROPAs through the transmission fiber in co- and counter-propagating directions, respectively and the residual pump power from each ROPA was cycled to its co-located partner.

However, this "enhancement" of the ROPAs optical scheme does not result in a significant additional budget increase for cases other than single channel transmission.

It is also important to point out that in our scheme there is no optical path connection between the output of the Tx ROPA and the input of its co-located Rx ROPA, thus avoiding potential signal crosstalk between the East-West and West-East fibers in contrast to the design proposed in [8].

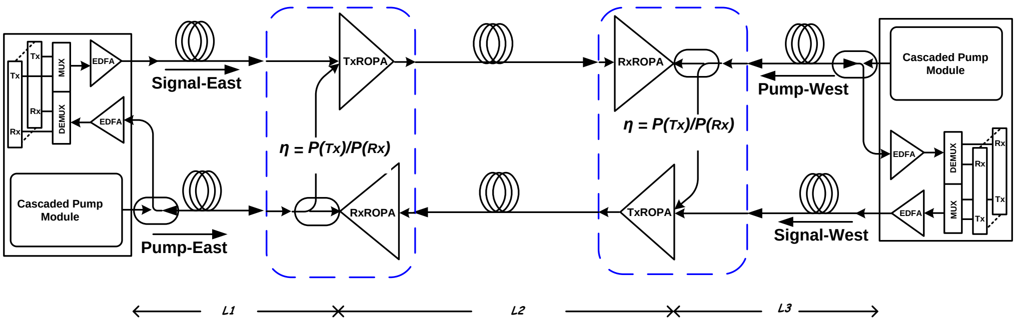

Figure 2. Pump-sharing concept

Both Tx and Rx ROPAs are placed in the same enclosure. Part of the pump power travelling "East" towards the Rx ROPA (amplifying signals travelling "West") is spilt off at the common ROPA location and is used to pump the Tx ROPA. Thus, the "West-East" transmission fiber is used for pump delivery to the "East-West" Tx ROPA (and vice versa). This scheme avoids co-pumping penalties associated with pump power delivery to the Tx ROPA

2. Budget estimation

The link consists of three fiber segments: ***L1***- from the pump source (receiver side) to the common location where part of the pump power is split between fibers and ROPAs; ***L2*** - between the Tx and Rx ROPAs and ***L3 = L1*** - from the transmitter to the co-located ROPAs. The total link length is: ***L = L1 + L2 + L3 = 2L1 + L2*** and so the link loss budget is:

$$B(\text{dB}) = 2B1 + B2$$

We'll estimate the link budget with optimal location of the Tx&Rx ROPAs and compare it with a link with an optimally positioned Rx ROPA alone. It is obvious that, for a given fiber loss, the maximum distance between a ROPA and pump launch point increases with increasing launch power. However, as mentioned previously, the maximum value of the pump power that can be launched is limited by the Raman gain produced by the pump (see Figure 1). One can assume that when both Tx and Rx ROPAs are located at the optimal distance from the terminals, the Tx ROPA should provide an output signal power approximately equal to the limit (***Pnl***) imposed by non-linear effects, including the non-linear phase accumulated in segment ***L1***, and the pump power at the Rx ROPA should be sufficient to provide adequate gain (typically ~20 dB) and noise figure performance of the amplifier.

These conditions can be fulfilled with a proper choice of the split ratio (Figure 2):

$$\eta = P_{Tx} / P_{Rx} >> 1$$

where P_{Tx} and P_{Rx} are the pump powers delivered to the Tx and Rx ROPAs, respectively. Under these assumptions, the loss in ***L3*** = ***L1*** from the terminal to the common ROPA location can be written as:

$$B1 = \varepsilon(P_0 - P_{Tx}) = \varepsilon[P_0 - Pnl + 10\log(\xi)]$$

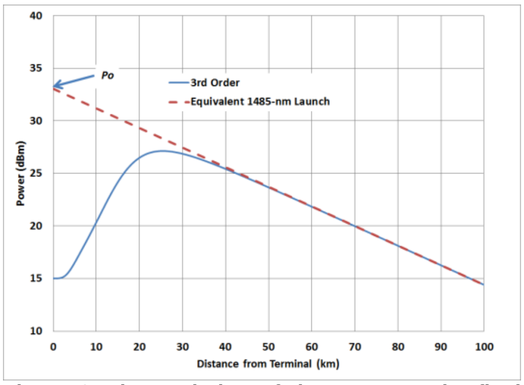

Figure 3. The evolution of the power at the final 1485-nm ROPA pump wavelength for 3rd order pumping – solid line, equivalent direct 1485-nm launch case – dotted line

where P_0(dBm) is the effective launch pump power which is indicated in Figure 3 which shows the evolution of the power at the final 1485-nm ROPA pump wavelength for 3rd order pumping along with that for the equivalent "effective" direct 1485-nm launch case, ***Pnl***(dBm) is the maximum signal launch power limited by the nonlinearity, ξ is the Tx ROPA efficiency and $\varepsilon = \alpha_s/\alpha_p$ is the ratio of the losses (in dB/km) at the signal and pump wavelengths.

The maximum tolerable loss of the ***L2*** link segment from the transmit to the receive ROPA is basically defined by the sensitivity of the Rx ROPA & the Transponder Receiver combined, which leads to a minimum acceptable signal power at the Rx ROPA input, denoted as ***Psens***(dBm). Therefore, ***B2*** is given by:

$$B2 = Pnl - Psens$$

Thus, the total link budget can be estimated as follows:

$$B_{Tx\&Rx} = 2B1 + B2 = 2\varepsilon[P_0 - Pnl + 10\log(\xi)] + (Pnl - Psens)$$

Using the same assumptions and definitions, the budget of the link with only a Rx ROPA is:

$$B_{Rx} = Pnl - Psens + \alpha_s L_0$$

Here, $\alpha_s L_0$ is the loss of the receive fiber segment for an optimally-positioned Rx ROPA alone. Therefore, the budget increase $\Delta B = B_{Tx\&Rx} - B_{Rx}$ provided by the optimization of the Tx&Rx ROPA combination is:

$$\Delta B = 2\varepsilon(P_0 - Pnl) + 20\log(\xi) - \alpha_s L_0 \quad (1)$$

For 3rd order pumping and a single 100 GHz QPSK signal in standard fibers, we can estimate the expected budget increase assuming realistic numbers as follows: $P_0 \approx 33$ dBm (see Figure 3), $Pnl \approx 14$ dBm, $\alpha_s L_0 \approx 20$ dB and an efficiency of the Tx ROPA $\xi \approx 0.6$.

$$\Delta B \sim 10 \text{ dB}$$

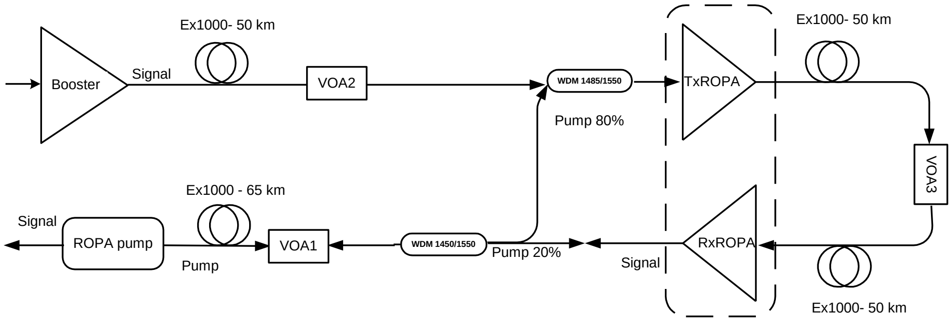

Figure 5. Experimental set-up

In other words, by adding to the design of a Rx ROPA alone configuration a length of Er fiber, a tap-coupler and a WDM, one can expect an increase of ~ 10 dB in link budget for the cost of a few standard passive components.

An important feature of equation (1) is that this budget improvement does not depend on the transponder receiver sensitivity i.e. the required OSNR. Therefore, the same improvement will be seen for all transponders and modulation formats which have a similar ***Pnl***.

The magnitude of the improvement Δ***B*** depends on the position of the common ROPA enclosure which in turn affects the optimum split ratio ***η***.

A modeling example of the additional budget increase ***ΔB*** vs. distance from the landing point to the common enclosure and with the split ratio for each location chosen to ensure 8 dBm of pump power for the Rx ROPA is shown on Figure.4.

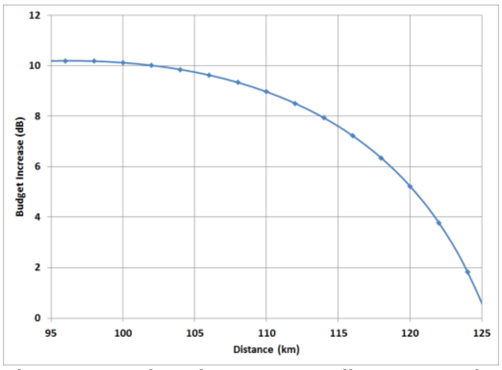

Figure 4. Budget increase vs distance to the Tx&Rx ROPA enclosure compared to a link with a Rx ROPA alone. Single 100 GHz channel.

3. Experimental set-up

For the experimental link (see Figure 5), in addition to the lengths of transmission fiber, variable optical attenuators were placed in each of the link segments (***L1, L2 and L3***), making it possible to accurately maximize the total link budget by varying all losses (lengths) and also keeping ***L1 = L3***.

Corning Vascade EX1000 fiber with an average loss of 0.165 dB/km was used for all link segments. Transmission experiments were carried out with Ciena's WaveLogic-3 transponders with a single interface supporting DP-QPSK 100 G and 50 G BPSK modulation formats. In each case, the transmission of one and then two channels was investigated. The initial single channel was at 1557.36 nm and the wavelength of the added second channel was 1555.75 nm. An MPB Er booster amplifier with an output power up to 26 dBm was used to amplify the signal(s). The ROPAs were pumped by a standard MPB 3rd order ROPA pump module with an output power up to 4 W at 1276 nm. Cascaded Stokes wavelengths of 1360, 1420 and 1485 nm were sequentially amplified in the 65-km transmission fiber segment. The Raman gain provided by this module is shown in Figure 1 and the evolution of the 1485-nm pump power in Figure 3. The measurement procedure was as follows. The attenuation of all of the link components and then of the whole link were accurately measured using both an Optical Spectrum Analyzer and a power meter.

Preliminary modelling showed that the pump power split ratio between Tx and Rx ROPAs should be ~ 4:1. A WDM coupler providing the required splitting ratio and having an insertion loss at 1550 nm < 0.5 dB was installed. For each modulation format and number of channels, the longest reach possible without remote amplifiers was found by adjusting the signal launch power to the nonlinear limit ("No ROPA" curves in Figure 6). Then, the Rx ROPA was installed, optimal pumping conditions were found and the link budget was measured ("Only Rx ROPA" curves in Figure 6). Finally, "co-located" Tx & Rx ROPAs were installed. In this configuration, the distance to the mutual location of the ROPAs and the distance between them were optimized, as well as the signal launch power. It was found that the longest reach for all pump-sharing cases tested was achieved when the equivalent distance to the ROPAs was ≈ 100 km (taking into account VOA losses) and the optimal pump power delivered to this point was ≈ 26 mW. The BER, Q factor and OSNR vs link loss were measured for each case.

4. RESULTS AND DISCUSSION

As can be seen from the Figure 6a, for the single QPSK 100 G channel case, usage of the "shared" ROPA design provides a budget increase ***ΔB*** = 11 dB over the optimal configuration with only a Rx ROPA, and a budget increase of ~ 32 dB compared to the case with no ROPAs. The total reach was ***B*** = 84.7 dB for a BER of 2.2 x 10^{-2} and Q = 6.05 dB, which is

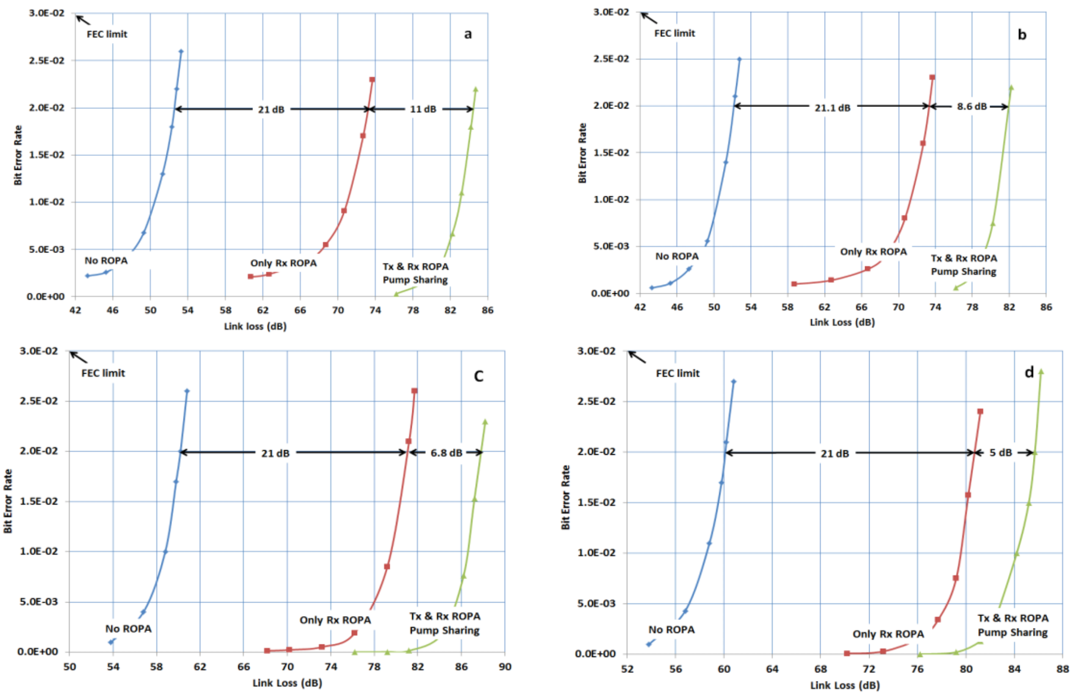

Figure 6. Bit error rate vs link budget of 1557.36 nm signal; a, b single and double DP-QPSK 100 GHz channels, c, d – single and double 50 GHz BPSK channels.

significantly below of the FEC limit of 3 x 10^{-2}.

In the case of two 100 G QPSK channels, Figure 6b, ΔB = 8.6 dB and B = 82.2 dB for a BER = 2.2×10^{-2} and Q = 6.16 dB.

The decrease of the budget improvement for the two channel case as compared to a single channel is directly linked to the division of the Tx ROPA output power between the two channels. Since the Tx ROPA pump power is the same for both cases, the distance between Tx and Rx ROPAs must be reduced. However, the difference is 2.5 dB (not 3 dB) because the efficiency of the Tx ROPA is slightly higher for the increased input signal power.

Preliminary measurements with 4 x 100 G QPSK channels resulted in a $\Delta B \sim$ 5.5 dB.

For the single 50 G BPSK signal, Figure 6c, the optimized “shared” ROPA configuration provides a budget of B > 88 dB for a BER < 2.2×10^{-2} and Q > 6 dB.

In this case, the budget increase compared to a Rx ROPA alone configuration is ~ 6.8 dB. The reason that the increase achievable for BPSK signals is significantly less than for QPSK channels is partially due to the fact that Pnl is ~ 3 dB higher for BPSK modulated signals and, in the Tx&Rx ROPA configuration, the signal power at the output of the Tx ROPA cannot be made high enough to take full advantage of this increased nonlinear tolerance.

With two 50 G BPSK channels, Figure 6d, ΔB = 5 dB and the budget is B =86.2 dB, which is 1.5 dB higher than for the single 100 G QPSK channel.

Alternative techniques for increasing link budgets include Raman co-pumping and the use of large-mode-area fibers. In links without a Tx ROPA, Raman co-pumping can increase the link budget by ~ 3-5 dB. However, using Raman co-pumping in links with a Tx ROPA actually does not substantially increase the budget because the reach is defined by the saturated output power of the Tx ROPA, which is ~ 50 - 60% of the delivered pump power and increases only marginally with increases in input signal power.

The link budget increase achievable through the use of large-mode-area fibers is proportional to the value of the effective mode area which is 1.5 to 2 times larger than in “normal” telecom fibers and thus the link budget can in principle be increased by 4 to 6 dB thanks to higher signal launch powers, and higher Tx ROPA output powers if the link is so equipped, as well as increased terminal-to-Rx ROPA distances for cases with a Rx ROPA. Usage of the proposed optimized ROPA configuration for transmission in standard G.652 fiber with a single pump module and one submarine enclosure per fiber could in many cases provide a reach that is higher or comparable with configurations using large-mode-area fibers plus Raman co-pumping and a Rx ROPA.

5. CONCLUSION

A new method for increasing reach in links with ROPAs that does not require additional active pump sources nor additional submarine enclosures has been proposed and investigated. It has been shown that a simple and inexpensive addition to the ROPA design and optimization of its location can provide an increase in reach up to ~ 10 dB compared to links with a Rx ROPA alone both for QPSK and BPSK modulation formats. This method could be used as well in ROPA links with large mode area fibers and provide similar additional budget increase ΔB.

6. Acknowledgement

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7. REFERENCES

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