# AMPLIFICATION TECHNOLOGIES SUPPORTING UPCOMING MODULATION FORMATS IN UNREPEATERED LINKS

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**Abstract**: This paper gives an overview over technologies that enable using higher order modulation formats supporting more than 100 Gbit/s per wavelength in existing unrepeatered systems. The advantages and disadvantages of these technologies are discussed. Placing a second ROPA close to the transmit side is the solution that potentially provides the required performance improvement. Therefore, the impact of important system parameters such as the position of the erbium-doped fiber coil, pump power, and pump wavelength on performance improvement is investigated.

## 1. INTRODUCTION

Unrepeatered transmission systems are attractive solutions for communication via optical fibers when the access to intermediate points is difficult or almost impossible. Typical applications are submarine links connecting islands with the mainland or with each other, but there are also use cases in terrestrial networks such as in desert, mountain, and forest areas. Elaborated amplifier setups installed at transmitter (TX) and receiver (RX) sides allow data transmission without intermediate amplification or regeneration. Additional advantages such as reduced cost of the cable and smaller weight due to the elimination of electrical power supply via the cable overweigh the increased cost associated with using more elaborated amplification schemes.

Combining high output power boosters with counterdirectional Raman amplification has been sufficient for transmitting 2.5 Gbit/s and 10 Gbit/s signals in currently deployed commercially used wavelength division multiplexed (WDM) networks. In special cases bridging longer distances, the optical signal-to-noise ratio (OSNR) has been increased by embedding remote optically pumped amplifiers (ROPAs) in the cable around 100 km apart from the RX [1-4]. With the trend to higher data rates such as 40 Gbit/s and 100 Gbit/s, codirectional Raman amplifiers and higher order Raman pumping schemes have been introduced in existing links in order to cope with the need for increased OSNR [4-6]. However, a new generation of transponders with data rates of 200 Gbit/s, 400 Gbit/s, and beyond is already in the wings [7-10]. The deployment of this new generation of transponders will be difficult using only the currently deployed amplification technologies.

In this paper, the advantages and disadvantages of available amplification technologies are assessed. Using a ROPA close to the TX side has probably the highest potential to support the new generation of transponders. Several important system parameters associated with the ROPA need to be optimized to extract the full potential from the ROPA. Therefore, the impact of ROPA position, pump power, and pump wavelength on transmission system performance is assessed.

## 2. AVAILABLE AMPLIFICATION TECHNOLOGIES

Various amplification technologies can be deployed simultaneously to extend the reach of unrepeatered transmission systems. The selection of the amplification technologies to deploy depends mainly on the distance that has to be bridged and the modulation format that is selected. Furthermore, some technologies are suitable for green field installations only. Typical combinations of amplification technologies in commercially deployed transmission systems are listed in Table 1.

| | Amplification technology at TX side | Amplification technology at RX side |
|---|---|---|
| (7) | Codirectional Raman amp | ROPA close to RX (higher order) |
| (6) | Codirectional Raman amp | ROPA close to RX |
| (5) | High power booster (EDFA) | ROPA close to RX (higher order) |
| (4) | High power booster (EDFA) | ROPA close to RX |
| (3) | Codirectional Raman amp | Counterdirectional Raman amp |
| (2) | High power booster (EDFA) | Counterdirectional Raman amp |
| (1) | High power booster (EDFA) | Preamplifier (EDFA) |

**Table 1. Typical combinations of amplification technologies in commercial unrepeatered system**

In the basic configuration, the channel power is adjusted by means of a **high output power booster** to a power level providing optimum balance between OSNR and nonlinear fiber effects. Using lower power levels leads to reduced OSNR while increasing the power level above the optimum one also leads to performance degradation since the increase of the nonlinear penalty overwhelms the benefit from improved OSNR.

Distributed Raman amplification is a favorite technology to improve performance of installed links since no component in addition to the fiber needs to be integrated into the cable. Thanks to stimulated Raman scattering, optical power is transferred from shorter wavelengths to longer wavelengths. The maximum power transfer efficiency is achieved when the pump and data signals are spaced apart by about 100 nm [11]. Therefore, the pump signals are usually transmitted in the 14xx nm window (1st order pumping), namely at around 1420 nm and 1450 nm.

In a first step, typically **counterdirectional Raman amplification** is used by launching one or more pump signals into the fiber from the receiver side. In this way, efficient amplification of the data signals is achieved.

Replacing the high power booster by **a codirectional Raman amplifier** gives some further reach extension. In this case, the pump signals are launched into the optical fiber from the transmitter side. However, the performance improvement achieved with this approach is smaller than the one achieved by counterdirectional Raman amplification. In order to maximize the benefit of this amplification scheme, the booster output power needs to be reduced as compared with the basic configuration.

Both amplification technologies can benefit from higher order pumping schemes transferring the pump power via some intermediate lightwaves to the data signals. In commercial systems, schemes up to the **third order** with lightwaves located in the 12xx nm range, around 1360 nm and 1450 nm have been used. The use of the higher order pumping in a codirectional configuration has the advantage of further reducing the impact of fiber nonlinearities at equal OSNR as compared with a first order pumping configuration. However, this technology might enhance the impact of imperfections of the pump on signal quality.

**Remote optically pumped amplifiers (ROPAs)** comprising a piece of erbium doped fiber (EDF) embedded into the link are used for a long time in challenging links that cannot be bridged with the techniques described so far. Energy for amplification is provided by a pump signal that is launched into the transmission fiber at the receiver side and propagates counterdirectionally to the signal. This pump signal will also interact with the data signals along the transmission fiber before reaching the EDF coil as in the case of counterdirectional Raman amplification. However, the power transfer from the pump to the data signals along the transmission fiber will not be as efficient as in the case of the counterdirectional Raman amplification configuration since the pump signal used with the ROPA is usually at around 1480 nm, instead of being in the 1420 nm - 1460 nm range. The 1480 nm wavelength is chosen because it leads to a good power conversion efficiency in the EDF coil and experiences lower attenuation in the transmission fiber. The optimum position of the EDF coil is usually around 100 km away from the RX side for typical transmission fibers [3]. Additional performance improvement can be achieved by higher order Raman pumping schemes. However, improved performance is achieved only when pushing the EDF coil further away from the RX [3].

Techniques described so far have been used widely in commercial installations. In contrast, **remote amplification close to the transmitter** has mainly been used in some hero experiments. A reason for this is the increased complexity of the design of transmission systems using such TX ROPAs due to the higher power levels of the data channels close to the transmitter side. Furthermore, codirectional ROPAs are less efficient than their counterdirectional counterparts. Nevertheless, the use

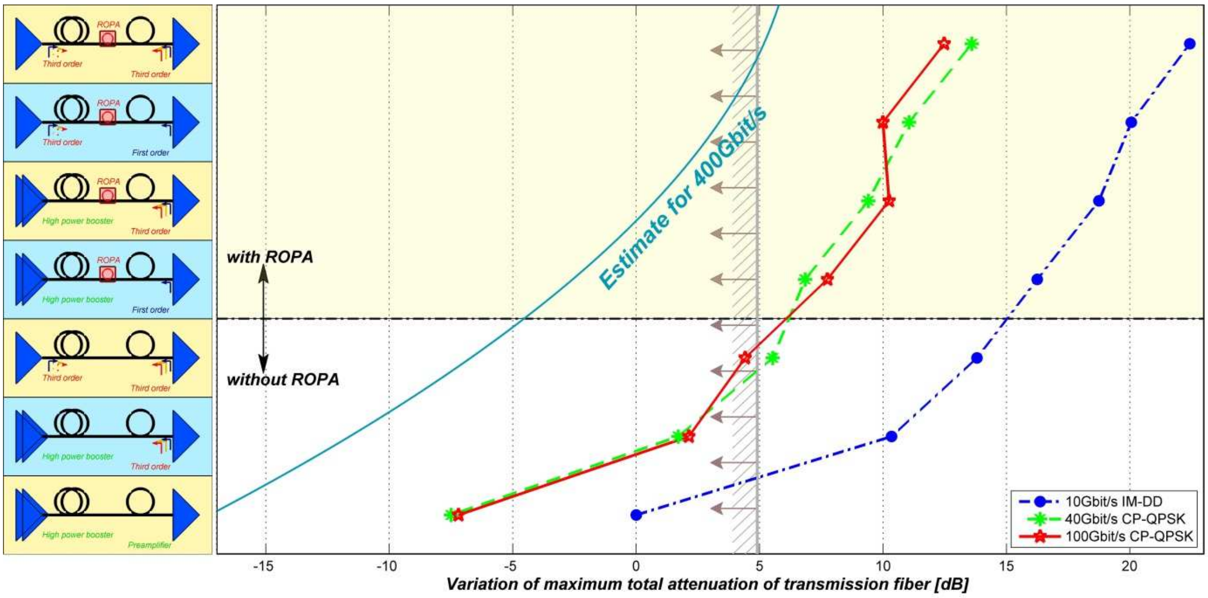

**Figure 1. Reach improvement provided by different combinations of amplification technologies when using different modulation formats as compared with the basis configuration operated with 10 Gbit/s channels**

of this amplification configuration may be the key enabler for deploying the upcoming modulation formats (200 Gbit/s, 400 Gbit/s and beyond).

## 3. IMPACT OF MODULATION FORMAT

Cost for installing the different amplification technologies increases with the chronological order of their presentation in the preceding section. For a given link, complexity and cost of the required amplifiers typically increases with data rate.

Figure 1 shows the reach improvement for 10 Gbit/s intensity-modulated signals with direct-detection (IM-DD) as well as polarization-multiplexed signals with coherent-detection and quadrature phase-shift keying (CP-QPSK). Typical combinations of amplification technologies, with increasing complexity from the bottom to the top, have been analyzed for the transmission of 32 channels in a pure silica core fiber (PSCF), characterized by an attenuation parameter of 0.177 dB/km at 1550 nm. The reach improvement is indicated relative to a basic configuration transmitting 10 Gbit/s signals and using erbium-doped fiber amplifiers (EDFAs) at the terminal sites only. The results have been obtained by means of simulations, whereas some data points have been verified experimentally. The optical power levels are optimized for each case.

Using 10 Gbit/s IM-DD signals, the maximum link attenuation can be increased by around 14 dB simply by using a combination of codirectional and counterdirectional Raman amplification. Additional 10 dB can be gained by embedding an EDF coil in the link. For an improvement up to 6 dB, even no distributed codirectional Raman amplification is required and a first order counterdirectional Raman amplifier is sufficient. In contrast, a combination of codirectional Raman amplification and third order counterdirectional Raman amplification is needed to transmit 40 Gbit/s CP-QPSK signals over the same link. Although the sensitivity of 100 Gbit/s CP-QPSK signals is 2 dB higher as compared with 40 Gbit/s signals in back-to-back (B2B) configurations [12], the maximum reach is very similar for both modulation formats. This has been achieved by em-

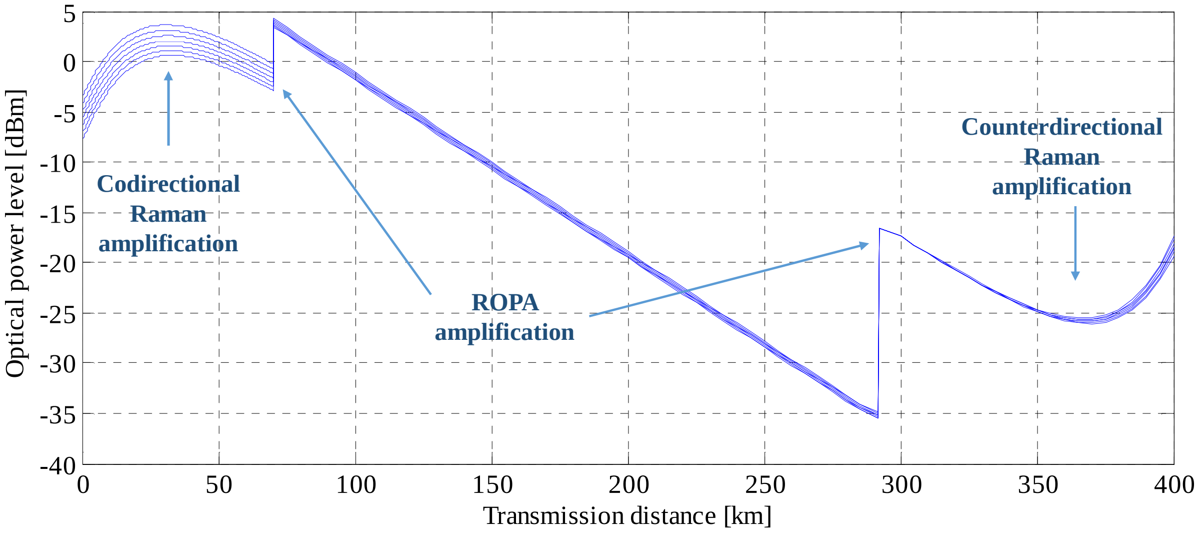

**Figure 2. Example of a power profile along an optical fiber when employing codirectional and counterdirectional ROPAs**

ploying better components and algorithms, such as soft decision feedforward error correction (SD-FEC), so that the resilience to transmission effects could be increased. In summary, significantly more complex amplification technologies have to be employed when transmitting CP-QPSK signals over links instead of 10 Gbit/s IM-DD signals.

Taking into account that the required OSNR in a B2B configuration for 200 Gbit/s and 400 Gbit/s signals is much higher than for 100 Gbit/s signals [12, 13] and that there are currently not ground breaking technologies in the loop that could compensate for the increased ONSR requirements, it is clear that additional amplification technologies will have to be deployed to achieve the same reach.

## 4. ROPA AMPLIFICATION ON THE TRANSMITTER SIDE

Remote amplification close to the transmit side has not been really explored commercially up to now, but has the potential to support the upgrade to transmission above 100 Gbit/s per channel. Figure 2 shows an example of the evolution of the optical power level of data channels that are amplified by two ROPAs, one pumped from the transmit side and the other one pumped from the receiver side.

Different implementations are possible. For example, a single pump wavelength or multiple pump wavelengths can be used. Furthermore, the pump power can be provided to the EDF via the transmission fiber or alternatively, if possible, the pump signal can be launched into a parallel fiber to be combined with the data signals at the input of the EDF. These different options are analyzed in this section in view of the achievable performance improvement. Reach improvement will be demonstrated for channels operating at 100 Gbit/s, since characteristics of such transponders are very well known.

**First order pumping scheme:** In this case, only one pump signal at 1480 nm is launched into the transmission fiber. In this section, the reach improvement achieved by this technique is always expressed as compared with a configuration using the same kind of amplifier at the receiver side, but with a high power booster at the transmitter side.

Figure 3 shows the reach improvement observed for sixteen 100 Gbit/s CP-QPSK channels transmitted in a PSCF when a ROPA is inserted close to the TX side for various positions of the EDF coil versus pump power launched into the fiber. The channel launch power is optimized for each scenario. About 2.5 dB of reach improvement can be attained when using the ROPA. Maximum reach improvement is achieved when the EDF coil is placed at about 20 km away from the TX side. Shifting the EDF coil deeper into the transmis-

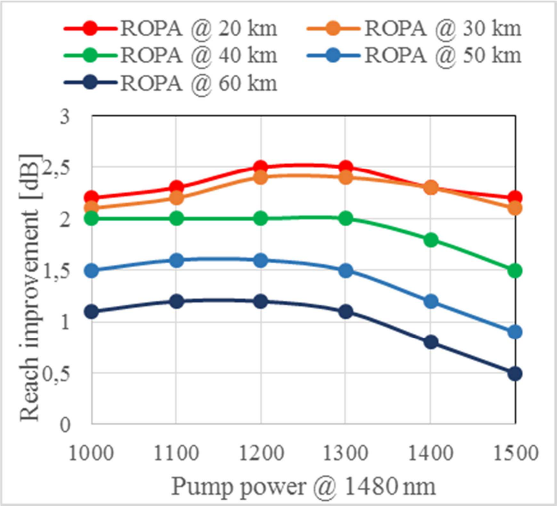

**Figure 3. Reach improvement versus distance of the EDF coil from the TX when using a single pump at 1480 nm for amplifying sixteen 100 Gbit/s signals in a PSCF**

sion fiber does not improve performance. Indeed, pushing the EDF away from the transmitter requires to increase the pump power in order to maintain the gain of ROPA. However, this increase leads to higher power transfer from the pump to data channels in front of the EDF coil. Therefore, the launch power of data channels needs to be decreased in order to keep the nonlinear degradation at a low level. Furthermore, the pump depletion along the PSCF counteracts to the increase of the pump power launched into the fiber resulting in worse performance.

Figure 4 shows the maximum reach improvement as a function of the number of channels when a ROPA is placed 30 km or 50 km away from the TX side (pumped at 1480 nm). The optical power levels of the pump and data channels are optimized for each scenario. The reach improvement obtained with a codirectional Raman amplification (2 pumps at 1426 nm and 1454 nm, respectively, with 550 mW output power each) is also depicted in Fig. 4 for reference. The curves in Fig. 4 show that using codirectional Raman amplification provides a similar reach improvement as using a TX ROPA when a large number of channels (>15) are transmitted. Additional results confirm this conclusion. Thus, the use of a ROPA on the transmitter side is not recommended for larger channel counts.

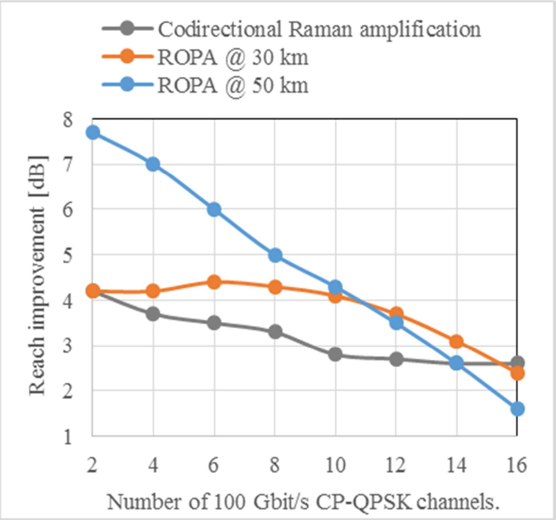

**Figure 4. Reach improvement as a function of the channel count for a TX ROPA with different positions of the EDF coil and for codirectional Raman amplification**

On the other hand, and as depicted in Fig. 4, a ROPA may indeed provide some reach improvement if the number of channels is small. In this case, performance improvement is very sensitive to the ROPA position. For example, an EDF placed 50 km away from the TX provides a performance improvement that is about 2.5 dB higher than positioning it 30 km away from the TX when transmitting 4 channels only. However, a major drawback is that upgrading such a system to high channel counts is almost impossible. In fact, the reach improvement for 16 channels is 1 dB smaller as compared with placing the ROPA 30 km away from the TX side. Moreover, the performance will be worse than using codirectional Raman amplification only.

Higher reach improvement has been observed for smaller channel count. This result was already expected because, at smaller channel count, the impact of nonlinear effects and depletion of the pump is smaller which allows the ROPA to provide higher gain and therefore, leads to an effective reach improvement.

**Higher order pumping scheme:** Since the depletion of the pump signal is one of the reasons for the small performance improvement provided by a ROPA, using higher order Raman amplification should provide additional performance improvement.

| | Pump wavelength [nm] | | | EDF pos. [km] | Reach increase [dB] |
|---|---|---|---|---|---|
| | 1390 | 1420 | 1480 | | |
| Pump power [mW] | 1000 | 1000 | 100 | 20 | 2.5 |
| | 1000 | 1000 | 100 | 30 | 2.9 |
| | 1000 | 1000 | 100 | 40 | 2.5 |
| | 1000 | 1000 | 100 | 50 | 2 |
| | 1000 | 1000 | 100 | 60 | 1.6 |
| | 1200 | 700 | 100 | 20 | 2.5 |
| | 1200 | 700 | 100 | 30 | 2.9 |
| | 1200 | 700 | 100 | 40 | 2.6 |
| | 1200 | 700 | 100 | 50 | 2.2 |
| | 700 | 1200 | 100 | 20 | 2.6 |
| | 700 | 1200 | 100 | 30 | 3.0 |

**Table 2. Reach improvement for different ROPA configurations and the transmission of sixteen 100 Gbit/s CP-QPSK signals in a PSCF**

Table 2 depicts the reach improvement achieved by a second order pumping scheme for the TX ROPA. The analysis shows that about 3 dB performance improvement can be achieved when using higher order pumping schemes. Several additional ROPA configurations have been tested. However, the maximum reach improvement achieved in those cases was also of the order of 3 dB. These results indicate that using a higher order pumping scheme can provide additional performance improvement, but it is quite limited (smaller than 1 dB with respect to first order Raman amplification).

The results shown in this section indicate that using ROPA amplification close to the TX side does not provide significant performance improvement when 16 or more channels are transmitted since almost the same performance improvement may be achieved using codirectional Raman amplification only. This result seems to be in disagreement with the findings presented in [14-15] where it is shown that placing a ROPA on the TX side (133.7 km away from the TX side) provides a performance improvement of 4.6 dB over codirectional Raman amplification. Moreover, codirectional Raman amplification was already able to provide 10.3 dB of performance improvement before placing the ROPA in the link. However, these results have been obtained for the transmission of a single channel over a PSCF. Indeed, it is shown in [14] that increasing the channel count to 4 channels already reduces the total reach by 5 dB. Although part of this reach reduction may be attributed to multi-channel nonlinearities, the major contribution is most likely arising from the smaller performance improvement provided by the codirectional Raman and ROPA amplifications.

**Transmission of the pump signal via a dedicated optical fiber:** Providing the pump power via a dedicated optical fiber completely removes the impact of pump depletion by data channels in front of the EDF coil, which is one of the most limiting effects when using a ROPA close to the TX side. Furthermore, nonlinear signal distortions induced by the high power pump are avoided. The main drawback of the approach is that an additional optical fiber is required in the part of the cable from the transmitter to the EDF coil.

Figure 5 shows the reach improvement obtained when transmitting sixteen 100 Gbit/s CP-QPSK channels over a PSCF and an EDF coil pumped at 1480 nm is inserted on the TX side, but with the pump signal being provided by a dedicated optical fiber. Only the impact of fiber attenuation is taken into account for the pump signal. Therefore, the presented results should be seen as an upper bound since additional propagating effects may impair the pump signal transfer. Significant reach improve-

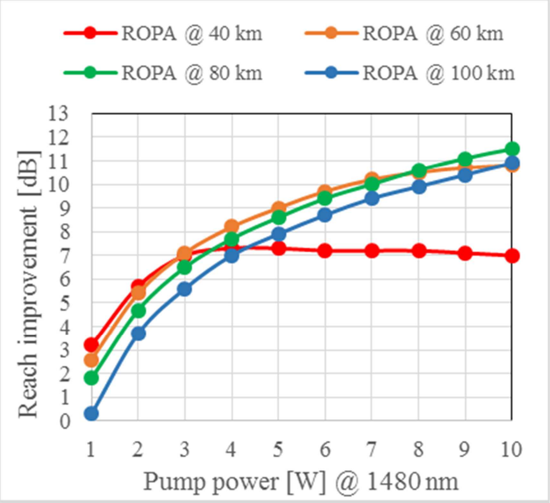

**Figure 5. Reach improvement achieved by placing a TX ROPA supplied with energy via a dedicated fiber at 4 different positions for the transmission of sixteen 100 Gbit/s CP-QPSK signals over a PSCF**

ment – even more than 10 dB – can be achieved with this configuration.

The main difficulty of this approach is to provide enough optical pump power to the EDF coil. Indeed, the EDF coil should be pushed deeper into the optical fiber in order to achieve higher performance. However, this requires larger pump powers. Please note that it may not be possible to provide the high optical pump power considered in Fig. 5 using commercially available components. Furthermore, the probability of destruction of the fiber by a fiber fuse increases with increasing pump power [16]. However, this problem might be overcome by using fibers with larger mode field area for providing the pump power. Furthermore, special optical fibers with lower attenuation at the pump wavelength allow to achieve the same reach improvement with smaller launch powers.

Nevertheless, at least 6 dB of reach improvement (pump power of 3 W, with ROPA placed at 40 km from TX side) may be already obtained using this amplification approach. Moreover, codirectional Raman amplification can also be used (in the optical fiber carrying the data channel), which will further increase reach.

## 5. CONCLUSIONS

Available amplification technologies for unrepeatered transmission system have been analyzed in view of the achievable performance improvement in order to support the transmission of upcoming modulation formats in existing links. Adding a ROPA close to the TX side is considered as the most promising candidate. However, typical ROPA configurations strongly suffer from transmission effects when larger number of optical channels (>14) are to be transmitted and thus cannot provide the required performance improvement. Alternatively, it has been shown that if the pump signal is provided by a dedicated optical fiber, the gain provided by the ROPA can be quite high, even up to 10 dB (assuming the transmission of 16 channels). In this case, the main limitation is the optical power reaching the EDF coil.

Since the maximum launch power is limited due to different effects, fibers with small attenuation and large mode field area should be used for providing the pump power to the EDF coil.

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