Long Haul Communication using Hybrid Optical Amplifiers.

Kakumani Lakshmi Venkatesh, Sana Karthik, Sannithi Hitesh Kumar
Vellore Institute of Technology
Vellore , India

***Abstract*—In this paper the authors have investigated the performance improvement in long reach optical access system with hybrid optical amplifiers. The apparent options of optical amplification in wavelength division multiplexing systems include the distributed Raman amplifiers, erbium doped fiber amplifiers, and semiconductor optical amplifiers. In our case distributed Raman amplifier is located at the mid-span reach extender which allows for remote amplification in passive network nodes by distributing a Raman pump together with the data signals. In the case of only distributed Raman amplifier in long reach optical access system wavelength division multiplexing exploitation is inefficient. Combining the advantages of different amplifiers allows fast gain dynamics, simultaneous large bandwidth amplification, and the ability to provide gain at any wavelength. Degradation of optical signal quality is evaluated in 10 Gbit/s long reach wavelength division multiplexing optical access system with hybrid distributed Raman-erbium doped fiber amplifier and distributed Raman-semiconductor optical amplifier.**

***Keyword* —Raman amplifier; erbium doped fiber amplifier; hybrid amplifier; semiconductor optical amplifier; wavelength division multiplexing.**

I. INTRODUCTION

Demand for larger data speed capacity has been increasing exponentially due to the massive spread of Internet services. At the same time, the great development of the capability of digital technologies has made possible broadening multimedia services like high-definition television, video on demand, videoconferencing and others [1, 2]. A latter Cisco forecast shows that global Internet traffic will increase by a factor of four with video-rich services being the dominant traffic in coming five years [3]. Due to above mentioned facts bandwidth intensive applications and exponential Internet traffic growth are continuing to drive the development of high speed and high density optical fiber access networks [1, 4].

The continuously progressing convergence of the access and the metro networks is moving into the focus of research towards dense and cost-efficient optical access networks [5, 6]. The idea of increasing the length of an optical access networks is not new with many significant demonstrations in the last 20 years [1, 7, 8]. There are multiple approaches that have been realized for reach extension in optical access networks [2, 9]. One solution is to implement a mid-span reach extender, but it should be mentioned that reach extenders require power, maintenance and housing, but give a practical solution to certain deployment strategy [2]. Nevertheless, the high optical loss budgets that are bound to extended reach dense network architectures require extra optical amplification [6, 15]. One of the most popular solutions of optical signal amplification is the usage of erbium doped fiber amplifiers (EDFA). This type of amplifiers can provide high level of amplification coped with low noise figure (NF), but due to material characteristics amplifier gain is highly frequency dependent and can be obtained only in a specific wavelength band. Semiconductor optical amplifiers (SOA) are the most cost effective alternative to EDFAs, but this type of amplifiers produces great amount of amplified spontaneous emission (ASE) noise and other signal impairments. Nevertheless benefits include compactness and the ability to facilitate additional functionalities such as wavelength conversion and all-optical regeneration [1]. In contrast to SOAs and EDFAs, distributed Raman amplifiers (DRA) provide broad amplification spectrum, producing very little amplified signal distortions, even negative NF values can be obtained. But this type of amplifiers requires powerful pumping sources, thus the use of Raman amplifiers is not the most cost effective solution and in the case of only DRA in long reach optical access system wavelength division multiplexing (WDM) exploitation is inefficient .

Combining the advantages of different amplifiers allows fast gain dynamics, simultaneous large bandwidth amplification, and the ability to provide gain at any wavelength [1]. Degradation of optical signal quality is evaluated in multichannel 10 Gbit/s long reach dense WDM (DWDM) optical access system with hybrid DRA-EDFA and DRA-SOA amplification.

II. Simulation Model

To obtain investigation results OptSim 5.2 simulation software was chosen, hence this strong mathematical tool can ensure high accuracy results and handle simulations of complex multichannel transmission systems without the need for powerful hardware. This simulation tool uses the Split-step method to perform the integration of the signal propagation equation in optical fiber:

$$\frac{\partial A(t,z)}{\partial z} = \{L + N\}A(t,z)\,, \qquad (1)$$

where A(t, z) is the optical field, L is the linear operator responsible for the calculation of the impact of such linear effects as attenuation and dispersion, and N is the nonlinear operator, which reflects fiber nonlinearity. The calculation is processed dividing the link into small spans of fiber, with length equal to Δz, and obtaining the L and N operators separately [6]. There are two ways of applying the split-step method: time domain split step (TDSS) and frequency domain split step (FDSS). The two differ only in the way L is calculated. TDSS calculated L in the time domain, but FDSS – in the frequency domain. The nonlinear operator in both cases is obtained in the time domain. The effective implementation of TDSS is far more difficult to achieve, but it provides high accuracy results. As for FDSS, it is easier to implement, but intrinsic errors can arise during the calculation process, and this may dramatically drop the accuracy of the obtained results [6]. This is why for our simulation the TDSS method was chosen.

To reach the goal of this research a 10 Gbit/s 16 channel passive DWDM optical access system was created (see Fig.1), with non-return-to-zero (NRZ) encoding technique, on-off keying (OOK) modulation format, and 50 GHz channel spacing. Each of the 16 channel transmitters operates at its own frequency in range from 193.05 to 193.8 THz with 50 GHz spacing between channels, the power of each transmitter was 1 dBm. All of the 16 generated optical pulse sequences are combined at the optical line terminal (OLT) and transmitted through 72 kilometers of single mode fiber (SMF) with 0.2 dB/km attenuation and 16 ps/nm/km chromatic dispersion.

After processing through this SMF fiber the attenuated signal passed through the mid-span extender, where it is combined in the SMF2 with the pumping radiation of the DRA. The signal is amplified while processing a second SMF (SMF2), the length of which was varied in order to obtain the achievable transmission distance. In cases with DRA-SOA and DRA-EDFA hybrid amplifiers a discrete amplifier was placed in the mid-span reach extender between the SMF1 and SMF2, in such a way forming a hybrid amplifier. For dispersion compensation a dispersion compensating fiber (DCF) was used, which was placed after the SMF2. The length of fiber was varied in order to find balance between the amount of compensated dispersion and the amount of DCF insertion loss. The SMF2 and the DCF, together with the optical splitter are a part of the optical distribution network (ODN).

In order to asses amplifier performance and obtain the reachable transmission distances in systems with DRA, DRA-SOA and DRA-EDFA amplifiers, eye-diagrams of the detected signal at the receiver block were analyzed and bit error rate (BER) values were obtained in all 16 channels. To identify signal impairments, which are produced by SOA and EDFA

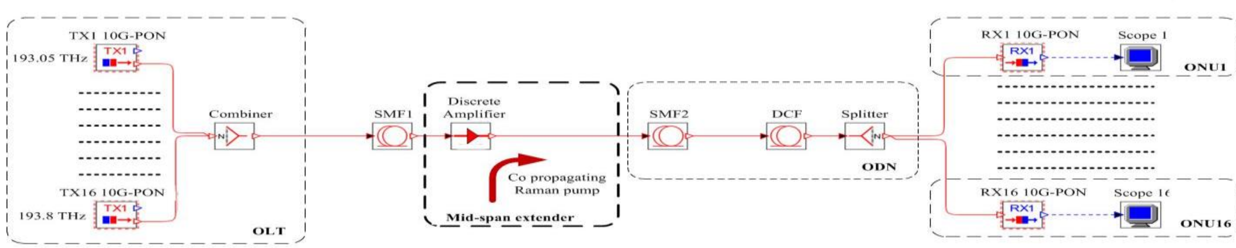

Fig. 1. Simulation scheme of the 10 Gbit/s long reach DWDM optical access system with hybrid DRA-EDFA and DRA-SOA amplification.

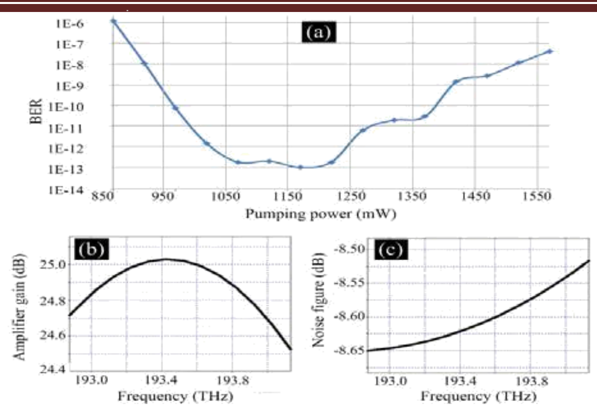

Fig. 2. System BER value dependence on the 1451.8 nm co-propagating pump power (a) of the DRA, and gain spectrum (b) and noise figure (c) of the DRA at 1150 mW pump power.

during amplification process, eye diagrams of a specific channel signal were analyzed at the input and at the output of these discrete amplifiers. For this matter the signal at the output of the amplifier was attenuated in order to compensate the amplifier gain. For assessing inter channel crosstalk, a transmitter of a specific channel was eliminated, and optical spectrum at the end of the link was observed. The parameters of amplifiers were optimized in order to obtain the maximal reachable transmission distance using a single in-line amplifier.

III. Results and Discussions

The aim of this section is to analyze and to compare results obtained in systems without amplification, with the DRA, with DRA-SOA and DRA-EDFA optical amplifiers.

To obtain the maximal reachable gain in transmission distance in systems with amplifiers mentioned above, it was necessary to obtain the reachable transmission distance in the system without amplification. To do so, the maximal length of the SMF fiber was obtained for which BER values of all 16 channels are below the 10-12 mark. The obtained results show that the maximal reachable transmission distance, for which this requirement is true, was 69 km. This transmission distance is highly dependent on the laser chirp, but this parameter was not taken into account because there was no opportunity to define this parameter in this simulation model, the value of frequency chirp at the Mach-Zender modulator was set to zero. For dispersion compensation a 5 km long DCF fiber was applied.

In case of the system with the distributed Raman amplifier, after adjusting the co-propagating pump wavelength it was decided to use a 1451.8 nm pump. Such pump wavelength ensures amplification, the peak of which coincides with the center wavelength of the 16 transmitted channel group. For obtaining the optimal pump power of the DRA BER values at the receiver end were observed. As can be seen from Fig.2.a the optimal pump power was 1150 mW. The growth of system's

BER values for pump powers over 1150 mW can be explained by the impact of nonlinear effects, especially four wave mixing (FWM). The obtained gain spectrum and noise figure (NF) of the DRA are shown in Fig.2b and Fig.2.c accordingly. It can be seen, that the peak of the obtained signal gain is around 25 dB and the maximal difference in amplification between channels is about 0.2 dB. The NF of the DRA is negative; this shows that due to the coherent nature of Stimulated Raman Scattering (SRS) the DRA can even improve the optical signal to noise ratio. Such high gain and low noise figure allowed to maintain the required signal quality (BER < 10^{-12}) over 146 km of transmission. To achieve such results a 1150 mW pumping source was required, such powerful laser is expensive. By lowering the power of the DRA and supplementing it with a SOA or an EDFA it is possible to acquire additional functionalities such as wavelength conversion and all-optical regeneration and obtain more uniform gain spectrum.

In the system with the DRA-SOA hybrid the material and the active layer parameters of the SOA were obtained from [18]. The single SOA parameter which was configured was the bias current, which was adjusted in order to obtain higher amplification coped with less amplifier produced signal distortions. The dependence of nonlinear multichannel distortions, which occur in the semiconductor, on the chosen SOA configuration is left for further investigation. 370 mA pumping current was chosen for this purpose. The rest of the signal gain was ensured by 350 mW 1451.8 nm co-propagating pump of the DRA. The power of the DRA for this hybrid amplifier was limited with signal distortions produced by the fiber nonlinearity. The level of amplification achieved by the SOA with 370 mA pumping current was 12.1 dB, and the 350 mW 1451.8 nm co propagating pump of the DRA produced 7.4 to 7.5 dB signal amplification. So the total gain achieved by the hybrid DRA-SOA amplifier in frequency range from 193.05 to 193.8 THz was from 19.5 to 19.6 dB.

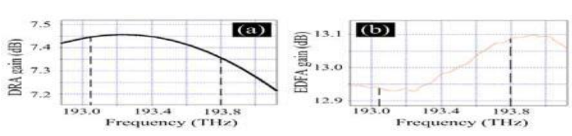

Figure 3. Gain of the DRA with 1150 mW 1458.1 nm pump (a) and of the EDFA with a combination of 10 dBm 980 nm co and 16 dBm 1480 nm counter-propagating pumps(b) in the hybrid DRA-EDFA amplifier.

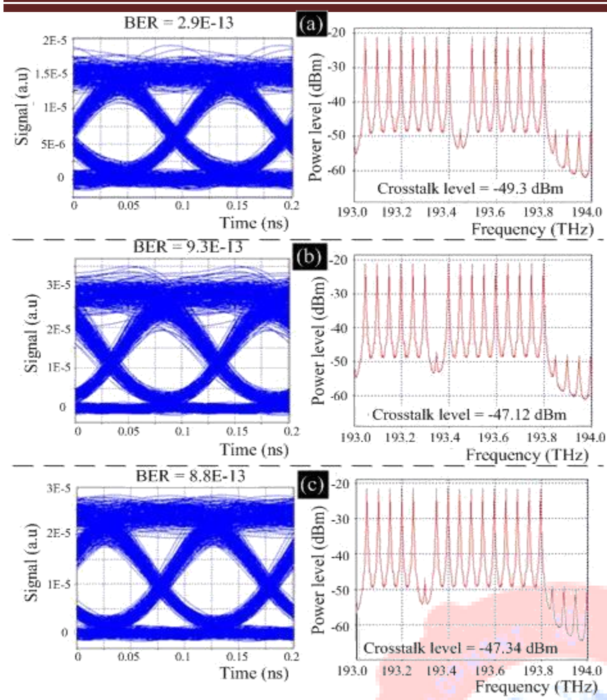

Figure 4. Eye diagram and inter channel crosstalk of the 9th channel of the system with the DRA (a), of the 7th channel of the system with the hybrid DRA-EDFA amplifier (b), and of the 6th channel of the system with the hybrid DRA-SOA amplifier (c).

This allowed increasing transmission distance to 124 km. The decrease in transmission distance was 22 km, but the supplementation of the DRA by the SOA helped to significantly lower the required pump power, and to obtain additional possible functionalities such as wavelength conversion and all-optical regeneration.

In the case of the DRA-EDFA hybrid amplifier, the EDFA was configured in order to obtain such gain spectrum, which could be easily equalized by a single pump Raman amplifier, so that the total amplification would be as even as possible for all of the 16 channels. It was determined, that for the system under test a 5 meter long doped fiber should be applied for such a purpose, and a combination of 10 dBm 980 nm co-propagating and 16 dBm 1480 nm counter-propagating pumps should be used to ensure the required level of population inversion. Such EDFA configuration ensured amplification in frequency range from 193.05 to 193.8 THz from 12.95 to 13.1 dB. As for the DRA, it was decided to use a 1453.1 nm 350 mW co-propagating pump to obtain the maximal transmission distance. The DRA amplified the signal from the EDFA output by 7.35 to 7.45 dB. The obtained gain spectra of the EDFA and the DRA can be observed in Fig.3. It can be seen, that by combining the gain spectra of the EDFA and the DRA, almost a perfectly even total gain spectrum is obtained. In fact, the total amplification achieved by the DRA-EDFA hybrid amplifier was about 20.4 dB ±0.05 dB, which is about 0.8 dB more than in the case of DRA-SOA. The obtained transmission distance in the system with the DRA-EDFA reached 126 km. This is 2 km more than in the case of the DRA-SOA. It is important to note, that the supplementation of the DRA with the EDFA not only has allowed to make the pumping power of the Raman amplifier a lot lower, but also helped to make the total gain spectrum more even in frequency range from 193.05 to 193.8 nm. The difference in amplification between all 16 channels is about 0.05 dB, which is by 0.15 dB less than in the case of a single DRA.

In order to identify the factors that caused such limitation of transmission distance, eye diagrams of the channels with the largest BER values at the receiver were observed. It was also important to obtain the levels of inter channel crosstalk in these channels at the end of the optical link. Eye diagram and inter channel crosstalk that correspond to the 9th channel of the DRA case, to the 7th channel of the system with the DRA-EDFA hybrid, and to the 6th channel of the system with the DRA-SOA are shown in Fig. 4. As one could see from the results that dominant factor that limited transmission was the FWM produced inter-channel crosstalk. Other nonlinear effect, such as cross-phase modulation (XPM)

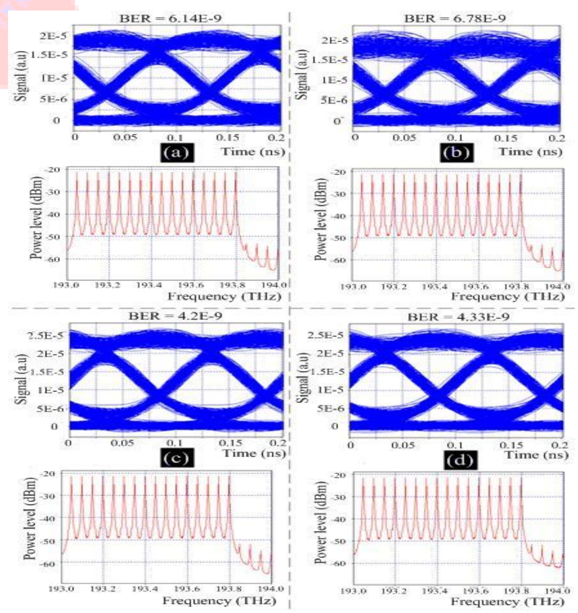

Figure 5. Eye diagrams and spectrums at the input (a,c) and at the output (b,d) of the discrete amplifier: of the 9th channel of the system with SOA (a,b) and of the 15th channel of the system with EDFA (c,d).

also had impact on the quality of transmission, but this impact was not as explicit as in the case of FWM. The amplitudes of the FWM produced spectral components in all three cases were over 5 dB. In systems with the DRA and the DRA-EDFA solutions this inter channel crosstalk is clearly represented on the eye diagrams as the explicit elevations above logical "1" level. In the system with the DRA-SOA hybrid the thickness of the logical "1" level points out, that in addition to these FWM produced signal distortions ASE noise also had great impact on the quality of transmission.

If we compare the systems with the hybrid amplifiers, in both cases the pumping power of the DRA was the same. So the difference in the total transmission quality can be explained only by the SOA and EDFA performance. In the case of the DRA-SOA the total amplification was about 0.8 dB lower, thus also the amount of inter-channel crosstalk should be lower. Still the DRA-EDFA hybrid had shown better results. This can be explained by significant signal distortions generated by SOA, even though it was intentionally configured to obtain higher gain coped with less noise. To get a clear view on the types of signal distortions that were generated by the SOA and the EDFA in hybrid amplifiers, the eye diagrams and spectrums at the input and at the output of this device with equalized power levels were observed (see Fig. 5) for the worst channel. After comparing the eye diagrams before and after propagating through the SOA it was noticed that it not only generates a large amount of ASE noise, but also produces signal phase distortions. This is pointed out by the fact that the transactions between the logical "1" and logical "0" have become thicker. The fluctuations above logical "1" level have become higher, this shows that inter channel crosstalk has become more explicit. It was concluded, that the factor that is responsible for the increase of inter channel crosstalk was FWM, and this showed that nonlinearity occurred in the semiconductor material. All of these SOA produced signal distortions have become the main reason for the difference in transmission distance achieved.

After comparing the eye diagrams at the input and at the output of the EDFA no severe additional signal distortions were found, except for slight enlargement of inter channel crosstalk and minor increase of ASE noise. So the reason for decrease in transmission after implementing the DRA with the SOA or EDFA can be explained by the evolution of the amplified signal along the SMF2: in the case of a single DRA the whole amplification process was distributed, so the intensity level of the amplified signal has risen slowly over a longer span of fiber, and the obtained amplification was partially compensated by signal attenuation in this fiber. But in the case of the hybrid amplifier a large part of amplification was discrete and the amplified signal instantly caused nonlinearity to take place as soon as it entered SMF2.

IV. Conclusions

In this work we investigated the opportunity of enhancing transmission distance of the downstream in a multichannel 10 Gbit/s long reach DWDM optical access system by supplementing the system with three different mid-span optical amplification solutions: DRA, hybrid DRA-SOA and DRA-EDFA. Each of the so-called mid-span extenders had been tested as in-line amplifiers between the OLT and ODN.

In the system with the DRA the largest transmission distance was achieved – 146 km. It also was pointed out that the Raman amplifier produced very few signal distortions and difference in amplification among all 16 channels of about 0.2 dB, but to achieve this a 1150 mW pumping source was required. Such powerful pumping sources are very expensive, so we lowered the pumping power and supplemented the system with a SOA and an EDFA, in order to find a more cost-effective solution. As result we managed to lower the power of the Raman pumping source to 350 mW, which ensured just under 7.5 dB of amplification. The rest of the required signal gain was provided by the SOA and the EDFA. After implementation of the hybrid amplifiers we observed 22 and 20 km decrease in achievable transmission distance. It was concluded that this decrease in transmission is due to the nature of signal power evolution along the SMF2 fiber, which in cases with hybrid amplifiers resulted in higher impact of fiber nonlinearity. In all three solutions FWM produced inter-channel crosstalk was the main factor that limited amplification and hence also transmission distance, and the difference in transmission achieved is explainable by signal distortions produced by the discrete amplifiers.

If we compare the both hybrid solutions then the difference in transmission distance obtained is only 2km. In contrast to the EDFA, the SOA produced a variety of signal impairment, including a large amount of ASE noise even though it was eventually configured in order to obtain more gain compound with less signal distortions. In the system with the hybrid DRA-EDFA we obtained less difference in amplification between all 16 channels among all three solutions under test. So in this particular case the DRA-EDFA hybrid has proved to be the better solutions, but due to the EDFA's strict gain-wavelength dependence this may not be the most appropriate solution in systems where wider bandwidth is required. On the contrary SOAs have much wider gain spectrum and this type of amplifiers can be used also in the O optical band, hence it can also be used for the upstream solution. Our final conclusion is that hybrid DRA-EDFA and DRA-SOA solutions may be successfully implemented in passive optical networks to extend the achievable transmission distance. In thiparticular case the usage of DRA-SOA helped to enlarge transmission from 69 km to 124 km, and the implementation of the DRA-EDFA hybrid – to 126km.

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