Hybrid EDFA/Raman Amplification Topology for Repeaterless 4.48 Tb/s (40 x 112 Gb/s DP-QPSK) Transmission Over 302 Km of G.652 Standard Single Mode Fiber

Juliano Rodrigues Fernandes de Oliveira, Uiara Celine de Moura, Getúlio Eduardo Rodrigues de Paiva,
Alexandre Passos de Freitas, Luis Henrique Hecker de Carvalho, Victor Emanuel Parahyba,
Júlio César Rodrigues Fernandes de Oliveira, and Murilo Araujo Romero

***Abstract*—In this work we carry out a comprehensive experimental study on hybrid optical amplification topologies (based on first order Raman and Erbium doped fiber amplifiers) for repeaterless transmission of 112 Gb/s dual polarization-quadrature phase shift keying (DP-QPSK) enabling a 4.48 Tb/s (40x112 Gb/s) transmission over 302 km of standard single mode fiber with coherent detection. Hybrid optical amplification was employed for signal boosting and pre-amplification and repeaterless transmission is assured without the use of neither in-line amplification nor remote optical amplifiers. The goal was to achieve the highest bandwidth-distance product for repeaterless DWDM transmission systems over legacy fiber without any in-line amplification technology. The achieved result is a significant milestone, when compared to recent state-of-the-art investigations.**

***Index Terms*—Coherent NRZ DP-QPSK, hybrid optical amplifiers, optical networks, repeaterless SSMF links.**

I. Introduction

REPEATERLESS systems are important in submarine networks as well as terrestrial spans in remote areas where inline service access is difficult to deploy. An increase on the transmission capacity often relies on advanced modulation formats, which are subject to stringent requirements with respect to the received optical signal-to-noise ratio (OSNR). In this case, an upgrade in the system capacity over a legacy infra-structure is only possible if the noise levels across the network are significantly reduced [1].

Since the large majority (over 80%) of terrestrial links is composed of SSMF ITU-T G.652 fibers [2], a feasible upgrade of legacy repeaterless spans requires the use of conventional fibers and commercially available pump power sources (first order pumps, in case of Raman amplification). For 10 Gb/s channel transmission through standard SSMF ITU-T G.652 fibers typical repeaterless spans are about 300 km, when coherent detection and electrical dispersion compensation are employed [3].

Recent investigations have reported multi-channel coherent 100 Gb/s transmission up to 462 km. However, those transmission arrangements made use of enhanced and/or ultra large area pure silica core fiber (ITU-T G.654) [5]–[7], or True Wave reach fiber (ITU-T G.655.C) [1], rather than standard single mode fibers (SSMF ITU-T G.652). Also, fairly sophisticated amplification schemes were needed, including high order Raman amplification and remote optically-pumped amplifiers (ROPAs) [4]–[7], as well as erbium-ytterbium doped fiber booster amplifiers, to provide an output power of about 30 dBm [5], [6].

However, when the goal is an upgrade of legacy terrestrial links from 10–40 Gb/s to 100 Gb/s channels, those approaches may not be a feasible option. This occurs because they rely on the use of unusual optical fibers, additional fibers to provide remote amplification, and high order Raman amplifiers [3]–[6], excessively increasing the overall system cost.

As an alternative, we propose the use of hybrid optical amplifiers composed of first-order Raman amplifiers and erbium-doped fiber amplifiers (EDFAs), as booster and pre-amplifiers respectively, to improve the legacy fiber (SSMF) span noise performance, aiming to achieve the highest possible bandwidth-distance product for 112 Gb/s repeaterless legacy fiber transmission systems. Such hybrid configurations are attractive because they can reduce the overall OSNR (compared to a topology using only EDFAs).

Specifically, in our work, hybrid optical amplifiers (EDFA/Raman amplifiers) were used to improve the channel OSNR, and coherent detection was used to achieve better sensitivity. The accumulated chromatic dispersion (CD) along the transmission path was mitigated in two ways, through the use of dispersion compensation modules (DCM) based on dispersion compensating fibers (DCF), as well as by electronic CD compensation through a time domain equalizer (TDE) algorithm [8], [9], carried out through off-line digital signal processing.

We were able to demonstrate both single-channel transmission as well as a 40-channel WDM experiment. The achieved

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J. R. F. de Oliveira, U. C. de Moura, G. E. R. de Paiva, A. P. de Freitas, L. H. H. de Carvalho, V. E. Parahyba, and J. C. R. F. de Oliveira are with CPqD Foundation—Research and Development Center in Telecommunications, Campinas, SP 13086-902, Brazil (e-mail: jrfo@cpqd.com.br; umoura@cpqd.com.br; gpaiva@cpqd.com.br; afreitas@cpqd.com.br; lhecker@cpqd.com.br; victorp@cpqd.com.br; julioc@cpqd.com.br).

M. A. Romero is with the Electrical and Computer Engineering Department, University of São Paulo, São Carlos, SP 13566-590, Brazil, (e-mail: murilo.romero@usp.br).

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span distance of 302 km for 40 channels (1353 Tb-km bandwidth-distance product) is a significant milestone on 112 Gb/s repeaterless transmission over standard single mode fiber (SSMF) ITU-T G.652 fiber and competitive when compared to state-of-the-art investigations. For example, in [10], a similar repeaterless WDM transmission with 12 channels at 120 Gb/s along 347.2 km G.652 fiber using pre dispersion compensation was reported, but resulting in a bandwidth-distance product, around 500 Tb-km. Also, [11] reports a careful cascade of two spans of slightly increased distance (303 and 343 km, respectively, of legacy submarine cables) but only 8 channels. In addition, in the same conference, [12] conducts an excellent experiment, to report a quite longer span distance (445 km vs. 302 km, in our case) but uses a LEAF fiber to mitigate non-linearities as well as employs second-order Raman pumping and ROPA. In addition, a smaller aggregate capacity was achieved (3.2 Tb/s vs. 4.48 Tb/s, in our case).

In the following sections, we initially present a single-channel transmission experiment. The goal of this preliminary investigation was to determine the optimum link configuration for the coherent 112 Gb/s repeaterless transmission over standard single mode fiber. Next, in Section III, we describe our 40-channel WDM transmission results, employing the hybrid amplification scheme selected in the single-channel experiment. Section IV concludes the paper.

II. SINGLE CHANNEL EXPERIMENT

A. Amplification Topologies and Dispersion Compensation Schemes

Fig. 1 depicts the experimental single-channel set-up employed to preliminary determine the optimum amplification arrangement and dispersion compensation schemes. In our experimental procedure, we used legacy SSMF fibers (G.652) with attenuation coefficient of 0.196 dB/km and chromatic dispersion of 17 ps/nm/km at 1550 nm and tested optical links from 100 km to 302 km in increasing steps of 50 km. The goal is to find the longest repeaterless span to transmit the 112 Gb/s DP-QPSK channel. For short spans scenarios (up to 200 km), not all amplifier technologies illustrated in Fig. 1 were necessary, as will be further discussed below. For each span length, we investigated two different chromatic dispersion compensation schemes. The first scheme compensates the chromatic dispersion using compensation fibers modules (DCF/DCM), comprising the lumped Raman amplifier of the receiver hybrid amplifier (the DCF length depends on the span length). The second scheme removes the lumped Raman amplifier and uses only a digital chromatic dispersion compensation TDE algorithm [9] at the coherent receiver digital signal processing (DSP) block.

In an overview, the set-up illustrated in Fig. 1 comprises the 112 Gb/s transmitter, the hybrid optical amplifier at the transmitter side, the fiber span, the hybrid amplifier at the receiver end, and the 112 Gb/s coherent receiver. Between the hybrid pre-amplifier and the receiver, a variable optical attenuator is placed to control the input power level. In addition, an optical passband filter (PBF) was used to reduce the level of amplified spontaneous emission (ASE) noise reaching the receiver. The next paragraphs describe in detail each one of these blocks.

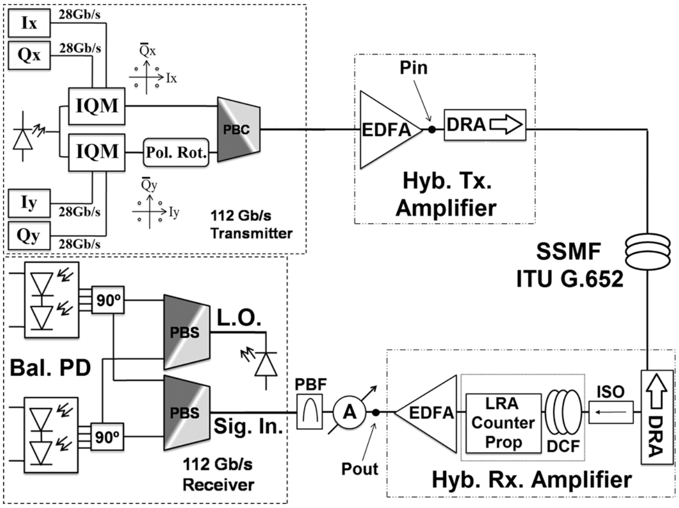


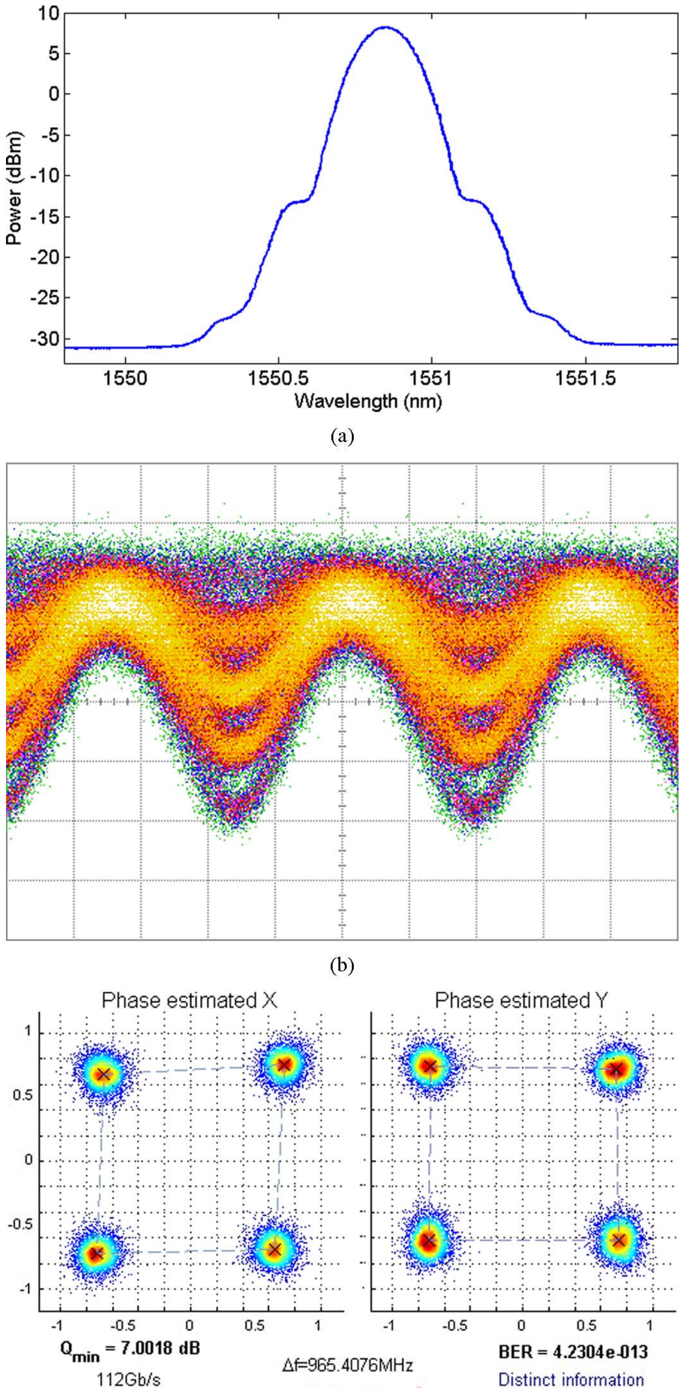
Fig. 1. Schematic illustration of the single-channel repearterless transmission system over standard fibers employing EDFA/Raman amplification for 112 Gbits/s NRZ DP-QPSK and coherent detection.

At the transmitter side, the signal (1549.48 nm wavelength) was inject into a 1×2 splitter. Each one of its output ports are connect to an in-phase and quadrature modulator (IQ modulator). Each branch of these IQMs receives an input bit rate of 28 Gb/s (based on pseudo-random bit sequences of $2^{31} - 1$), resulting in two 56 Gb/s signals at each IQM output. Next, one of the IQM signals passes through a polarization rotator, in such a way to produce two orthogonal polarized signals, combined by the polarization beam combiner (PBC) as illustrated in the transmitter block in Fig. 1. In the end, the transmitter block provides a $-10\ \mathrm{dBm}$ signal at 1549.48 nm, modulated by a 112 Gb/s NRZ DP-QPSK data stream.

At the receiver side, the signal enters into a polarization beam splitter (PBS) in order to separate both signal polarizations. The same process is carried out for the local oscillator (LO), which uses a wavelength of 1549.48 nm, linewidth of 150 kHz. Next, both polarizations, for the signal and LO, are directed to 90° optical hybrids. Following the hybrids, the balanced photodetectors translate the optical signals from the optical domain into the electrical domain, also converting the 112 Gb/s stream into four streams of 28 Gb/s each. Then, to receive the data, off-line DSP algorithms were employed over the four 28 Gb/s data stream, aiming the compensation of linear effects (with steps of deskew, orthonormalization, chromatic dispersion (CD) compensation, dynamic equalizer, frequency offset estimation and phase estimation) [13].

For the 112 Gb/s DP-QPSK channel, the maximum back-to-back OSNR was 37 dB with a measured pre-FEC BER of 4.23×10^{-13} (estimated from the Q factor). On the other hand, the minimum back-to-back OSNR needed to detect the signal with pre-FEC BER below the 3.8×10^{-3} FEC threshold was 13.4 dB (providing 2.9×10^{-3} of measured BER).

Fig. 2 shows the measured back-to-back signal for the 112 Gb/s DP-QPSK signal captured after the EDFA transmission amplifier ($\mathrm{P_{in}}$ spot at Fig. 1). Fig. 2(a) illustrates the transmitted 112 Gb/s DP-QPSK channel spectrum power with 37 dB OSNR

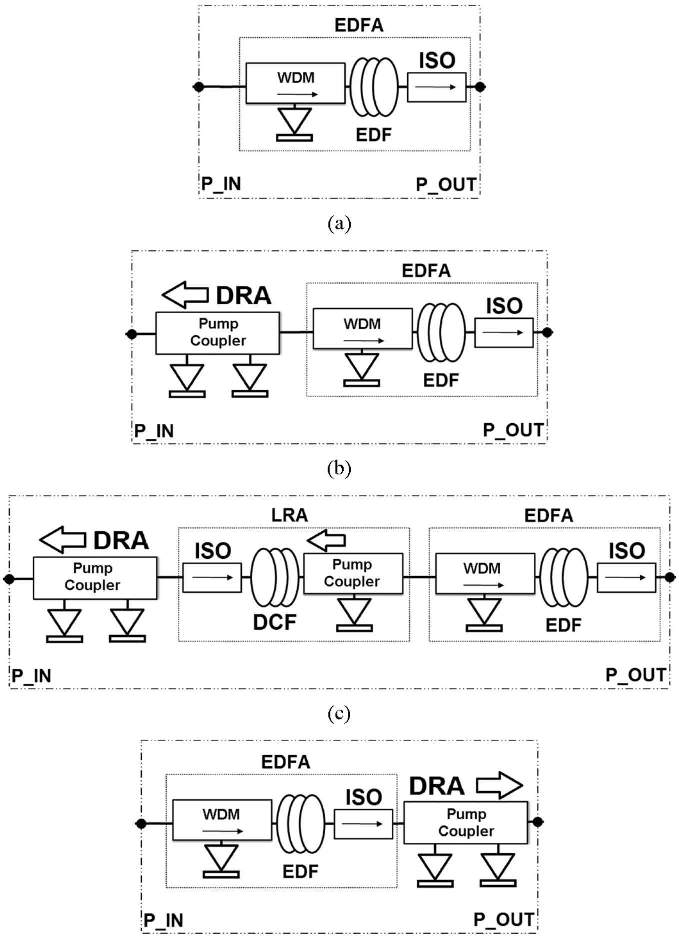


(a)

(b)

(c)

Fig. 2. Measured 112 Gb/s DP-QPSK back-to-back signal: (a) Power spectrum; (b) Eye-diagram; (c) Constellation.



(a)

(b)

(c)

(d)

Fig. 3. Amplifier topologies used on the experimental setup: (a) Transmitter EDFA ($\mathrm{NF} = 4.8\ \mathrm{dB}$); (b) Receiver Counter-propagating DRA/EDFA (equivalent $\mathrm{NF} = 2.1\ \mathrm{dB}$ at 100 km G.652 span); (c) Receiver Counter-propagating DRA/LRA/EDFA (eq. $\mathrm{NF} = 2.1\ \mathrm{dB}$ at 100 km G.652 span); (d) Transmitter EDFA/Co-propagating DRA (eq. $\mathrm{NF} = 2.1\ \mathrm{dB}$ at 100 km G.652 span).

while Fig. 2(b) illustrates the signal eye-diagram. Finally, in Fig. 2(c) the signal constellation after the off-line digital signal processing is shown, corresponding to a BER of 4.23×10^{-13}. The constellation quadrature error of Fig. 2(c) occurs because at the time of the single channel experiment the electronic circuit to make the automatic modulator bias control was not available. This forced us to manually adjust the modulator best operation point, producing quadrature errors after a while. The automatic modulator bias control was already available for the WDM experiments of Section III and the problem was eliminated.

Aiming to reach the longest G.652 repeaterless span with a single 112 Gb/s DP-QPSK channel system, we tested two chromatic dispersion (CD) compensation schemes for SSMF span lengths ranging from 100 km to 302 km. In the first scheme, CD was compensated through our TDE algorithm [13], which increases the number of filter taps accordingly to the transmission distance, in order to electronically compensate the chromatic dispersion. In the second scheme, a lumped Raman amplifier (LRA) was employed, using DCM/DCF modules as the gain medium to amplify the signal while optically compensating chromatic dispersion.

Regarding the optical amplifier schemes used to reach the longest possible repeaterless G.652 fiber span length for the transmission of a 112 Gb/s channel, we tested four distinct amplifier topologies (two transmission amplifiers and two receiver amplifiers, totalizing four different combinations) based on the amplifier schemes illustrated on Fig. 3.

For span lengths ranging from 100 km to 200 km, we tested two amplifier combinations. The first combination uses the booster EDFA depicted Fig. 3(a) at the transmission side while at the receiving side we used the DRA/EDFA hybrid amplifier showed on Fig. 3(b), compensating CD through DSP algorithms. The second combination uses the same booster EDFA as the transmission amplifier, but a DRA/LRA/EDFA hybrid amplifier depicted at Fig. (c) as the receiving amplifier, compensating the chromatic dispersion through the DCM/DCF of the LRA.

For span lengths of 250 and 302 km, two additional amplifier combinations were investigated. The third amplifier combination was the hybrid EDFA/DRA amplifier depicted at Fig. 3(d) as the transmission amplifier, with the DRA/LRA/EDFA hybrid amplifier showed on Fig. 3(c) as the receiver amplifier. The fourth amplifier combination used was the hybrid EDFA/DRA amplifier showed on Fig. 3(d) as the transmission amplifier, with the DRA/EDFA hybrid amplifier depicted on Fig. 3(b) as the receiver amplifier.

The selected EDFA provides maximum output power of 22 dBm with a noise figure of 4.8 dB. For both DRAs (co-propagating and counter-propagating), two Raman pumps were used, one at 1440 nm and the other at 1450 nm, each operating at maximum power levels of 360 mW, to provide an on-off gain of 8.6 dB for the co-propagating DRA and 15.9 dB for the counter-propagating DRA. All Raman pump lasers used was semiconductor continuous wave (CW) sources stabilized with FBG gratings with less than $-120\ \mathrm{dB/Hz}$ of relative intensity noise (RIN). The Raman pumps were combined with a polarization beam combiner integrated with depolarizer, to avoid polarization gain dependence on both co-propagating and counter-propagating Raman amplifiers. For the LRA we used a pump power of 150 mW operating at 1450 nm, capable to provide up to 6 dB of on-off gain. The DCF displayed attenuation coefficient of 0.63 dB/km, and chromatic dispersion of $-163.2\ \mathrm{ps/nm/km}$ at 1550 nm.

B. Results and Discussions

The several amplifier topologies described in the previous sub-section were tested on several lengths of repeaterless transmission spans (SSMF G.652 optical fiber) with a single 112 Gb/s DP-QPSK channel, aiming to find the longest possible reach. As explained previously, for spans ranging from 100 km to 200 km, the optical link configuration employs a booster EDFA at the transmission side, and a hybrid counter-propagating DRA/EDFA amplifier (CD compensation through DSP) or hybrid counter-propagating DRA/LRA/EDFA amplifier (CD compensation through DCM into the LRA) at the receiver side. Up to 200 km, these amplification schemes are enough to provide pre-FEC BER below 3.8×10^{-3}. We assumed a FEC code defined in ITU-T G.975.1, consisting of interleaved BCH(1020,988) with 10-fold interactive decoding [9] and allowing a coding gain of 8.8 dB, to set the error free transmission limit as 3.8×10^{-3}.

However, when the span length increases above 200 km (250 and 302 km respectively), the previously tested topologies do not provide sufficient system power and OSNR margins, causing severe degradation to the measured BER. Then, in a first step, the receiver amplifier configuration were kept unchanged, but we replaced the transmitter EDFA booster by a hybrid EDFA/DRA co-propagate amplifier. For the span length of 250 km, this scheme is capable to provide OSNR and BER values below the FEC limit. However, as it will be explained below, for 302 km of span length a further increase on the transmission hybrid amplifiers launch power to achieve the required BER within the FEC limit was needed.

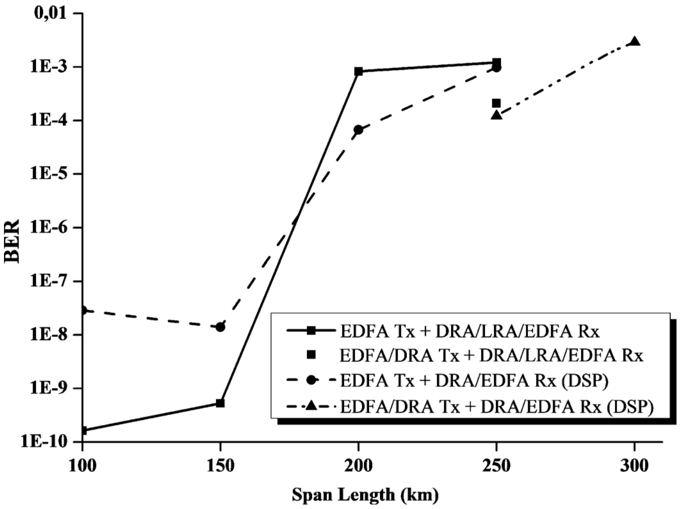


Fig. 4. BER versus SSMF transmission distance for a 112 Gb/s NRZ DP-QPSK channel. Results are provided with and without the use of DCFs. For distances greater than 250 km a co-propagation distributed Raman amplifier is also used at the transmission side.

In order to allow further understanding on the measured BER results, Fig. 4 illustrates the measured BER for all tested amplifier topologies and span lengths. For each measurement, we acquired 160 k samples by using 28 G symbol rate and 80 G samples per second, resulting in 1.78×10^{-5} of minimum count BER. For any value below this threshold, the BER value is estimated from the Q factor.

The longest span length achieved was 302 km, with OSNR of 14.1 dB and measured BER of 2.9×10^{-3}, which can be corrected to error free condition by means of a FEC code. Regarding the CD compensation method, it can be seen that for shorter fiber lengths, up to 150 km, better BER performance is obtained when the CD is compensated through the LRA (with DCM), in comparison to the DSP electronic compensation. In contrast, for longer fiber lengths (higher than 150 km) the use of DSP for CD compensation provides better BER results. This trade-off occurs because the DSP was configured with a high number of taps, and a larger cumulative dispersion is required to make the optimum compensation with the digital filter. Because of the larger filter size and higher tap count, our DSP algorithm works better for longer distances rather than for shorter distances.

On a side note, this improved performance for longer distances helps to explain the result of Fig. 4 (third case), in which we verified a BER drop at 150 km (1.4×10^{-8}) compared to 100 km (2.89×10^{-8}). This measurement artifact is also due to the lack of automatic bias control for the modulator combined to the fact that, for such low values, the BER is estimated from the Q factor (and the estimated BER could be slightly different from the real counted BER).

TABLE I
BER RESULTS AT 302 KM (SSMF) AND 112 GB/S NRZ DP-QPSK AS A FUNCTION OF THE OPTICAL POWER LEVELS

EDFA Output Power (dBm)	Raman 1440 nm Pump Power (dBm)	Raman 1450 nm Pump Power (dBm)	Raman Total Pump Power (mW)	BER
10.84	140	190	330	9.00x10-3
10.84	130	260	390	6.40x10-3
10.84	160	260	420	4.00x10-3
10.84	190	260	450	8.00x10-3
9.34	130	290	420	5.00x10-3
9.34	**160**	**260**	**420**	**2.90x10-3**
9.34	190	230	420	5.00x10-3
8.00	160	260	420	5.00x10-3

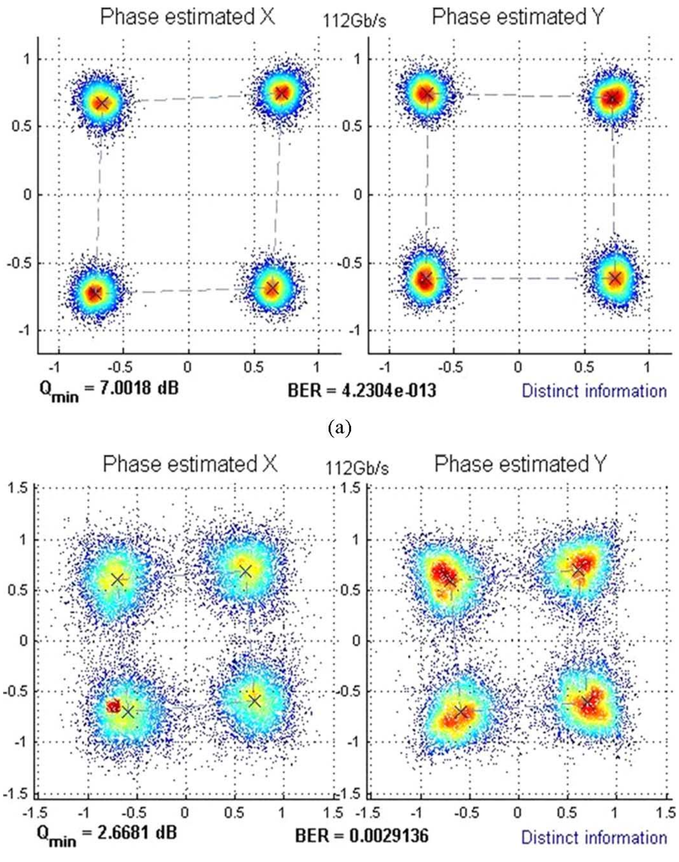
The launched power (transmission EDFA total output power) needed to reach the 302 km span was around 10 dBm, and it is the bottleneck to set the link-length upper limit. This high launch power was necessary to assure an enhance at the received OSNR in our long repeaterless span length, but fine adjustment is needed to provide the best trade-off between a healthy received OSNR and the onset of non-linear effects. In any case, the launched power in this repeaterless experiment is higher than used in amplified links (where typical launch powers range from $-3.5\ \mathrm{dBm}$ to 3.5 dBm [14], [15]) because non-linear effects are generated only once (as opposed to n times, for an amplified link of n spans) becoming less deleterious to transmission performance.

In our specific case, the transmission hybrid amplifier (EDFA/co-propagate DRA) output power and Raman pumping power trade-off values needed to provide the best received BER for the 302 km system are described at Table I. Setting the power levels to its maximum values would lead to very intense non-linear effects over the SSMF. For this reason the EDFA output power (at the site indicated by $\mathrm{P_{in}}$ in the schematic of Fig. 1) was reduced to 42% of the maximum value allowed. Also, the total Raman pumping power is 58% of the nominal available value.

In addition, for the 302 km span system, the high optical attenuation of the DCF prevented chromatic dispersion compensation through the LRA at the receiver hybrid amplifier, due the low OSNR received (below 13.4 dB). Then, for this case, the hybrid (counter propagate DRA/EDFA) receiver amplifier was operated at both counter-propagating pumps at nominal power (100%) and the EDFA optimized for operation as a pre-amplifier, i.e., to display the lowest possible noise figure. Chromatic dispersion compensation was carried out electronically, through digital signal processing (DSP).

The main difference between the transmitter and receiver DRA pump power levels for the 302 km span, was that the receiver Raman amplifier was configured to use the maximum pumping power while the transmitter Raman amplifier does not. This is mainly because the signal power level reaching the receiver DRA is too low when compared to signal power at transmission. Then the maximum counter-propagating DRA total pump power does not generate as much nonlinearities as the co-propagating one.

The back-to-back received constellation, related to the measured BER of 4.23×10^{-13}, is showed in Fig. 5(a). The equivalent result, after 302 km of signal propagation without repeaters, is showed in Fig. 5(b). The achieved pre-FEC BER was 2.9×10^{-3}.



(a)

(b)

Fig. 5. (a) Back-to-back constellation and (b) detected constellation after digital signal processing for the link of 302 km without repeaters. The achieved BER (2.9×10^{-3}) is within the FEC code limit.

Table I shows the BER measurements details, displaying the combination of output and pump optical power levels for the 302 km link. With the increase of co-propagating DRA total pump power from 330 mW to 450 mW, the BER decreases to 4×10^{-3} (420 mW of DRA total output power provided the best result), and then returns to higher values because the with the increase of DRA total pump power, non-linear effects over SSMF start to impair the signal.

As the signal wavelength is 1549.48 nm and the Raman gain peaks approximately 100 nm longer than the pump wavelength, the 1450 nm pump laser power must be higher than the one used at 1440 nm. Non-linear effects were minimized when the power ratio between Raman pump was 40%/60% (1440 nm/ 1450 nm). Then, still at Table I, decreasing the EDFA output power from 10.84 dBm to 8 dBm allows a BER decrease to 2.9×10^{-3}, followed by a return to higher values. An EDFA total output power of 9.34 dBm and co-propagating DRA total pump power of 420 mW provides the best tradeoff between high OSNR and low non-linearities.

III. REPEATERLESS 40-CHANNEL WDM EXPERIMENT

Fig. 6 illustrates the set-up put together to demonstrate the transmission of 40 WDM channels (50 GHz channel spacing

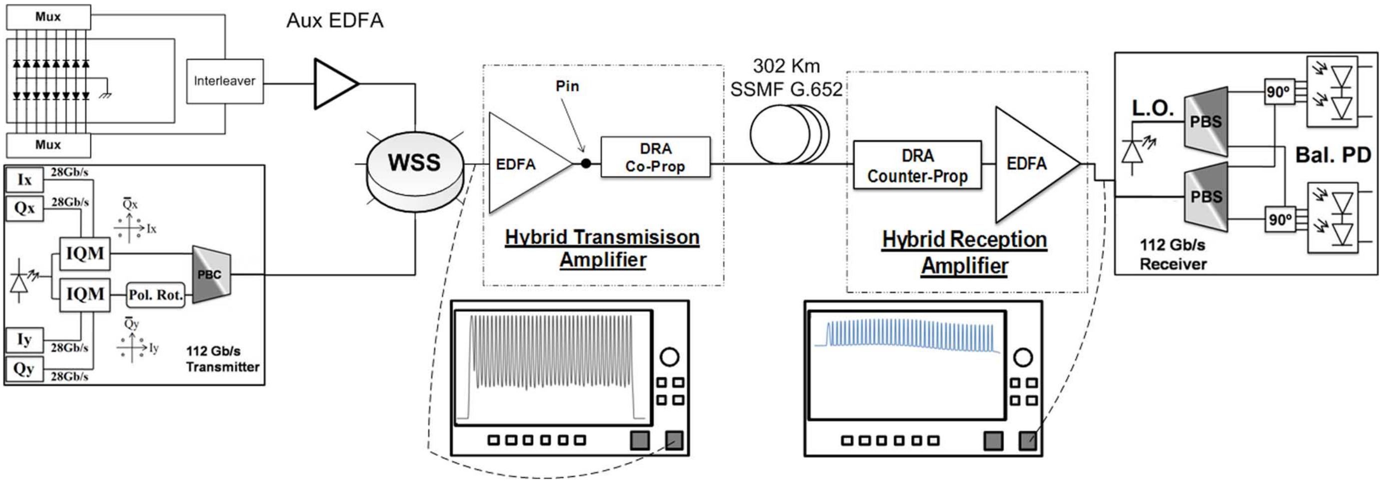


Fig. 6. (a) Back-to-back constellation and (b) detected constellation after digital signal processing for the link of 302 km without repeaters. The measured BER achieved (2.9×10^{-3}) is within the FEC code limit.

over the upper C-band spectral region) along the same 302 km of G.652 SSMF fiber and using the hybrid amplification scheme at the transmitter (booster EDFA/co-propagating DRA) and receiver sides (counter-propagating DRA/line EDFA) investigated in the repeaterless experiment of the previous section.

The experiment sought to find the maximum number of channels in a WDM signal that could be transmitted along the 302 km repeaterless span, simultaneously determining the hybrid amplifiers operation points to allow the minimum required OSNR, corresponding to a BER of 3.8×10^{-3}, within the FEC limit.

A. Setup Description and Amplifier Design

A WDM channels benchtop was used to populate the C-band. This benchtop was built combining 40 WDM odd CW channels by using an optical multiplexer while the corresponding 40 WDM even channels were input into another multiplexer. Both multiplexed outputs were then combined by an interleaver, to provide up to 80 WDM channels, as illustrated at Fig. 6. The benchtop channel frequencies range from 192.1 THz to 196.05 THz, on a 50 GHz channel spacing. An auxiliary EDFA booster (not part of our amplification scheme) was used to level the optical power of those benchtop wavelengths with the tunable 112 Gbps DP-QPSK modulated signal. An automatic modulator bias control was added to avoid constellation quadrature errors and this tunable modulated channel was used to evaluate the bit error rate (BER) within the C-band.

The tunable 112 Gb/s DP-QPSK signal and the amplified benchtop combo were multiplexed by means of a two port wavelength selective switch (WSS). The WSS carries out channel multiplexing and equalization, providing flattened channels at the WSS output port, as illustrated in Fig. 6. Next, the combined WDM output reaches the transmission hybrid amplifier, composed by the booster EDFA and a co-propagating distributed Raman amplifier (DRA), similar to those already described in the single-channel experiment of Section II. After transversing the 302 km G.652 SSMF repeaterless span composed of six fiber spools of 50 km spliced together, attenuation loss of 0.196 dB/km (plus five splices with 0.182 dB totalizing 60.1 dB of total loss) and 16.7 ps/nm/km of chromatic dispersion at 1550 nm. The signal reaches the hybrid receiver amplifier, again composed of a counter-propagating DRA and a line EDFA. Finally, the signal is detected by the coherent receiver and processed through our off-line DSP algorithms to recover the DP-QPSK constellation signal.

The experiment was initially performed using all 80 channels WDM signal (full C-band). However, even with careful adjustments of both hybrid amplifiers operation points in order to attain the best OSNR, it was verified that, after the 302 km repeaterless span, all the channel wavelengths belonging to the lower half of the C-band spectral range (blue band) reach the receiver with an OSNR below the minimum of 13.4 dB required for a pre-FEC BER below the FEC threshold. As a consequence, the number of WDM channels was reduced to find the maximum number of channels with at least 13.4 dB of OSNR, that was reached when we have 40 channels, populating the upper half C-band spectrum (red band), and the hybrid amplifiers were set to provide the best flatness with lower noise figure. In this case, the benchtop channels frequency ranges from 192.1 THz to 194.45 THz with 50 GHz channel spacing, and -3.5 dBm total output power (no spectral equalization).

The tunable 112 Gbps DP-QPSK transmitter illustrated at Fig. 6 provides 0 dBm of total output power. Thus, before multiplexing, it was the necessary to use the auxiliary booster amplifier (see Fig. 6) to level the benchtop channels optical power (per channel) with the 112 Gbps signal. Specifically, the booster EDFA was used to provide 23.5 dB of gain, thereby bringing the total WDM benchtop power to 20 dBm. Then, the modulated channel and the amplified laser benchtop were multiplexed at the WSS which attenuates properly the channel frequencies to equalize all channels. Considering its 8 dB insertion loss and 4.1 dB attenuated due the equalization process, the total available power at the WSS output was 8.1 dBm (-7.9 dBm per channel).

On the other hand, during the single 112 Gbps DP-QPSK channel experiment, we had determined that a hybrid amplifier configuration in which the EDFA-stage output of 9.34 dBm/

channel (in a single-channel experiment) provided the best results. Taking this as a design starting point and also adjusting the launch power per channel to reach the best result to the WDM experiment, the EDFA per channel best launch power was obtained for 9 dBm, which result that the EDFA stage in our hybrid transmitter amplifier must provide approximately 17 dB gain, resulting in 25 dBm of output power and lowest possible noise figure.

This was reached through the designed transmission hybrid amplifier (EDFA/co-propagating DRA) where the booster EDFA is composed by a two-stage configuration, to achieve 17 dB of nominal gain (flattened spectral gain) and 25 dBm output power. Each EDFA stage employs a 600 mW single pump at 980 nm. In between those stages, an intermediate custom GFF is placed for gain-flattening. The co-propagating DRA was built using two 360 mW pump lasers (1440/1450 nm), to provide additional 4 dB of on-off gain.

At the receiving end, the hybrid amplifier is composed by a counter-propagating DRA and a line EDFA. The counter-propagating DRA was built using two 360 mW pump lasers at 1440 nm and 1450 nm, respectively, providing 16 dB on-off gain. Considering the span loss of approximately 60 dB, the total power reaching the EDFA was around $-16.6\ \mathrm{dBm}$. In this context, the EDFA is a two-stage amplifier (pre-amplifier followed by booster stage), to provide high gain (26.2 dB) with enough output power (9.6 dBm).

B. Experimental Results

In our experiment, each one of the 40 CW WDM benchtop wavelengths was replaced (one at a time) by the 112 Gbps signal and the BER was measured (also each channel at a time). Measuring in this fashion (1 × 112 Gb/s channel plus 39 non-modulated channels) is accurate if transmission with all modulated channels is not affected by non-linear and cross-talk effects. In particular, with all channels modulated at 112 Gb/s with 50 GHz channel spacing, it is necessary to consider the following possible effects: self phase modulation (SPM), four wave mixing (FWM), intra channel cross-talk and cross-phase modulation (XPM).

The literature indicates that our measurement technique is correct. Specifically, the SPM related to each of the 40 modulated channels does not differ in nature to the SPM produced by the signal on itself [16]. Regarding the FWM, [17] demonstrated that FWM induces negligible impact compared to XPM (which is the dominant non-linear impairment) in SSMF coherent systems with 50 GHz spacing. In addition, [18] showed that the use of CW lasers (or non-intensity modulated channels) around a modulated channel, which is our tested configuration, actually represents the worst case as far as FWM effects are concerned. Regarding the channel cross-talk, [19] and [20] demonstrated that even with all channels modulated at 112 Gb/s DP-QPSK, with 50 GHz channel spacing, there is negligible penalty related to cross-talk between the transmitted channels when the received BER is near the pre-FEC limit. Finally, the XPM is the most relevant non-linear effect for 112 Gb/s DP-QPSK WDM transmission with 50 GHz channel spacing [17]. However, [21] demonstrated that spans using G.652 fibers, for lengths up to 640 km without in-line chromatic dispersion compensation, even considering all channels modulated at 112 Gb/s DP-QPSK with 50 GHz channel spacing, present a XPM penalty lower than 0.25 dB for all tested launch powers.

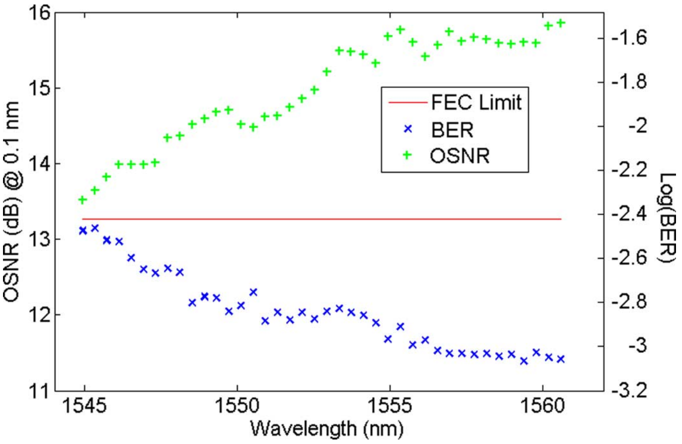


Fig. 7. OSNR (left axis) and BER (right axis) as a function of the channel wavelength.

Fig. 7 illustrates the BER and OSNR obtained by using the above mentioned technique. Inspection of Fig. 7 indicates that all 40 BER values are kept below the pre-FEC threshold.

The worst channel performances were at 194.05 THz (1544.94 nm, ITU grid H40) which shows the lower OSNR value (case 1) and at 194.00 THz (1545.30 nm, ITU grid C40) which shows the higher BER value (case 2). The best BER and OSNR were at 192.1 THz (1560.60 nm, ITU grid C21), referred to as case 3.

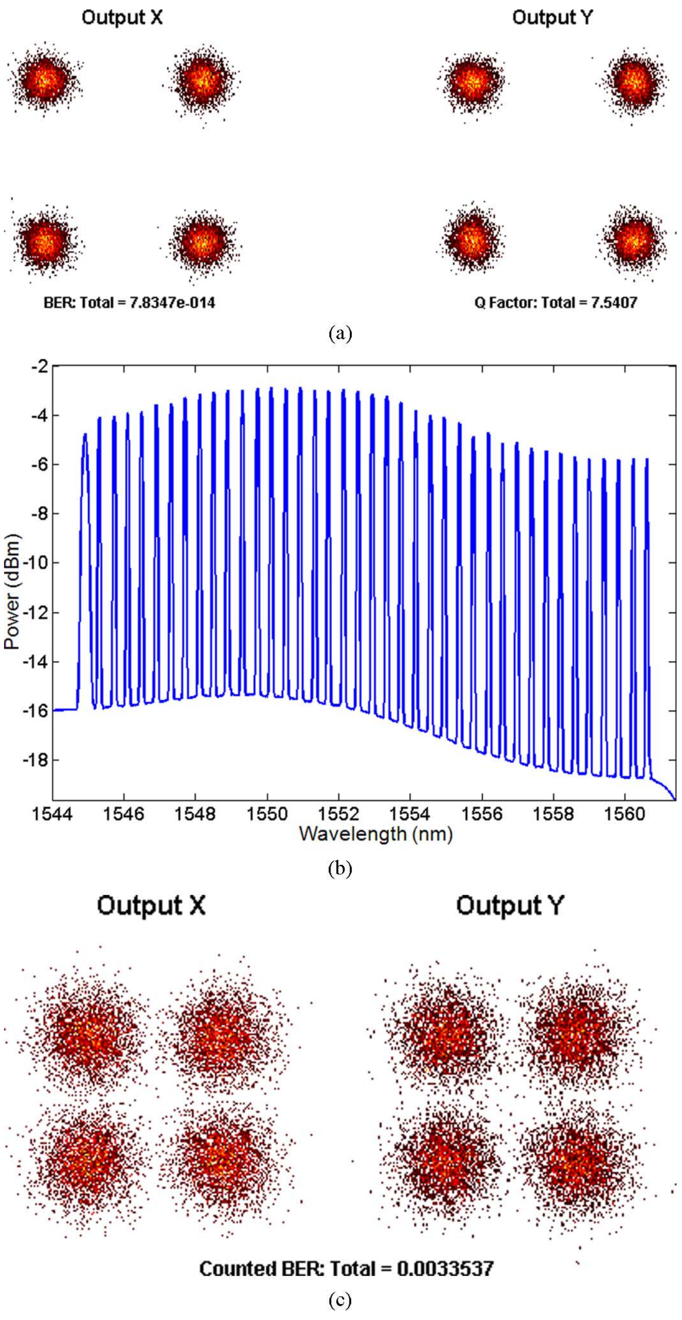
All channel frequencies lower the 194.05 THz display OSNR values below the required OSNR of 13.4 dB and cannot be detected in a error-free condition by the 112 Gbps DP-QPSK coherent receiver. On the other hand, considering case 2, it is possible to notice that the penalty induced by the interfering neighbors at both sides is not significant, placing the corresponding OSNR above the desired limit.

Figs. 8–10 illustrate the WDM optical spectrum and received signal constellations for each measured case (Fig. 8 also shows the back-to-back results, demonstrating that the use of the automatic modulator bias control allowed the elimination of constellation quadrature problems). It can be seen that all channels shows pre-FEC BER below the FEC limit (3.8×10^{-3}).

For case 1 (112 Gb/s at 194.05 THz/1544.94 nm/H40) illustrated at Fig. 8, the counted BER was 3.35×10^{-3}, the measured channel peak power was $-4.765\ \mathrm{dBm}$, the lowest peak power was $-5.814\ \mathrm{dBm}$ at 1559.82 nm (192.2 THz/ITU-T C22) and the highest peak power was $-2.863\ \mathrm{dBm}$ at 1550.12 nm (193.4 THz/ITU-T C34). The WDM spectral tilt was 2.951 dB.

For case 2 (112 Gb/s at 194.0 THz/1545.30 nm/C40) the counted BER was 3.44×10^{-3}, the measured channel peak power was $-4.696\ \mathrm{dBm}$, the lowest peak power was $-5.974\ \mathrm{dBm}$ at 1559.82 nm (192.2 THz/ITU-T C22) and the highest peak power was $-2.819\ \mathrm{dBm}$ at 1549.30 nm (193.5 THz/ITU-T C35). The WDM spectral tilt was 3.155 dB.

Finally, for case 3 (112 Gb/s at 192.1 THz/1560.60 nm/C21) the counted BER was 8.73×10^{-4}, the measured channel peak power was $-5.746\ \mathrm{dBm}$, the lowest peak power was



(a)

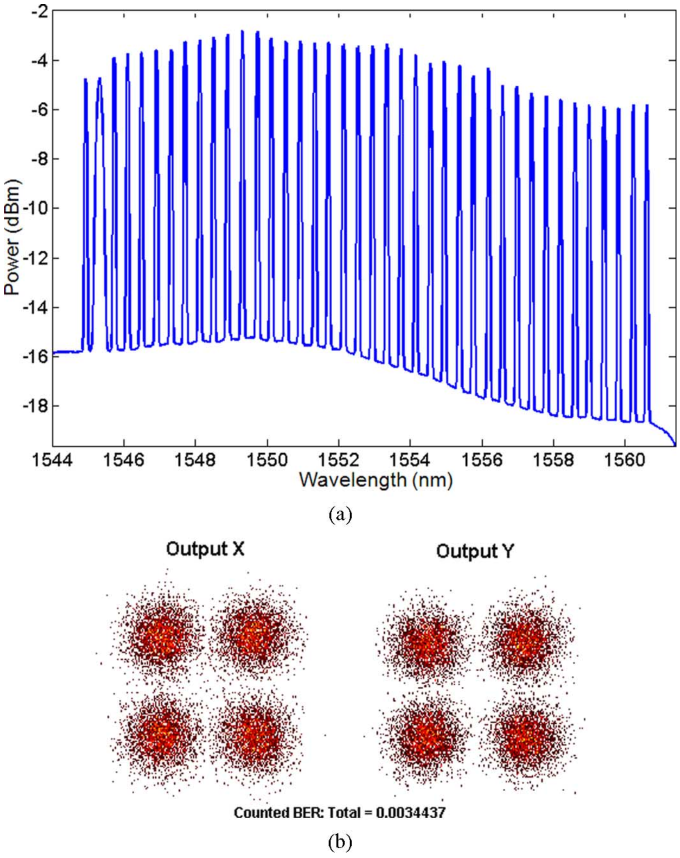
(b)

(c)

Fig. 8. (a) back-to-back received 112 Gb/s DP-QPSK signal constellation (b) Received WDM optical spectrum and (c) received signal constellation for case 1 (channel at H40).

$-5.974\ \mathrm{dBm}$ at 1559.4 nm (192.25 THz/ITU-T H22), and the highest peak power was -2.962 at 1549.74 nm (193.45 THz/ITU-T H34). The WDM spectral tilt was 3.012 dB.

Considering the worst (C40) and the best performance (C21) channels, the off-line received data was subject to the following non-linear compensation algorithms: digital back propagation (DBP) [22] and Maximum Likelihood Sequence Detection (MLSE) [23]. The goal was to evaluate the performance improvement offered by non-linear compensation as well as to identify which non-linear impairments are the most relevant in our transmission experiment.



(a)

(b)

Fig. 9. (a) Received WDM optical spectrum and (b) received 112 Gbps DP-QPSK signal constellation for case 2 (112 Gbps channel at C40).

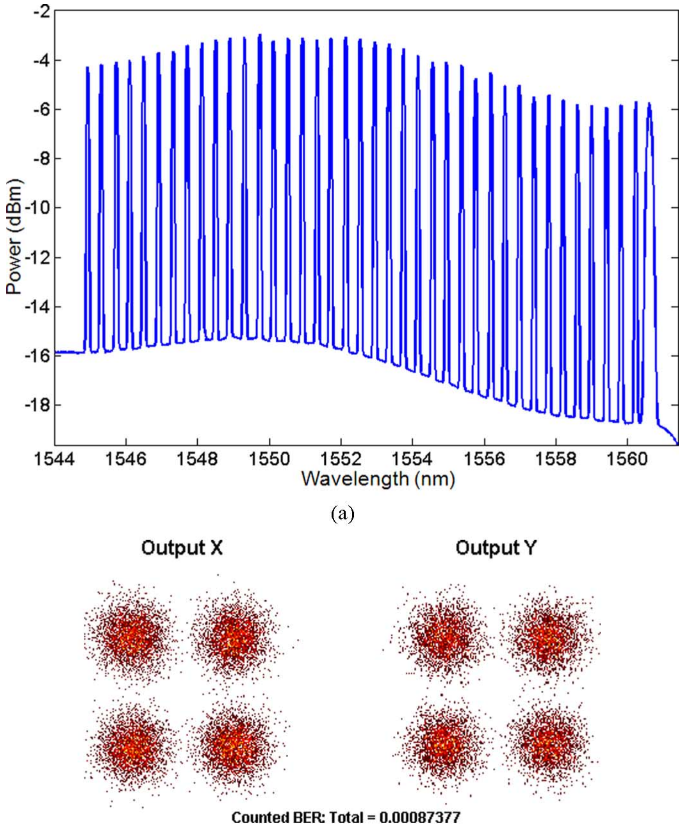
TABLE II
CHANNEL BER CONSIDERING DBP AND MLSE NON-LINEAR COMPENSATION

Wavelength (ITU Grid)	BER without non-linear compensation	BER with DBP	BER with MLSE
1545.30 nm / C40	3.4×10^{-3}	3.4×10^{-3}	1.9×10^{-3}
1560.60 nm / C21	8.7×10^{-4}	5.8×10^{-4}	2.5×10^{-4}

As it can be seen in Table II, using the DBP algorithm (which mainly compensates for the SPM effect) provides a BER improvement for channel C21 but not for channel C40. This is because the C21 channel is located at the spectral end of our WDM grid, thereby mostly affected by intra-channel Raman amplification from all other channels. The consequent increase on peak power enhances the SPM effect.

Also at Table II, when the MLSE algorithm was used, a improved BER performance was registered for both channels. This indicates that the MLSE algorithm capability to compensate SPM, XPM, FWM and residual CD is playing a significant role and those impairments are quite relevant in our experiment.

Finally, Table III compares both channels to the back-to-back reference (with and without non-linear compensation). Channel C40 suffered a 1.27 dB OSNR penalty without non-linear compensation (or using the DBP technique). By using the MLSE, the channel penalty is reduced to 0.59 dB, corresponding to a 0.68 dB OSNR gain compared to the case without non-linear compensation. For the C21 channel, the final penalty, when MLSE



(a)

(b)

Fig. 10. (a) Received WDM optical spectrum and (b) received 112 Gbps DP-QPSK signal constellation for case 3 (112 Gbps channel at C21).

TABLE III
Estimated Channel OSNR Penalty Related to Back-to-Back Condition (**Penalty** Improvement) With and Without DBP and MLSE

Wavelength (ITU Grid)	Without non-linear compensation (dB)	With DBP (dB)	With MLSE (dB)
1545.30 nm / C40	1.27	1.27	0.59
	ref.	**0.00**	**0.68**
1560.60 nm / C21	1.87	1.50	0.76
	ref.	**0.37**	**1.11**

is also used, is reduced to 0.76 dB (corresponding to 1.11 dB OSNR gain).

IV. Conclusion

We have carried out a comprehensive design study of hybrid amplifiers topologies to demonstrated the transmission of 40 channels at 112 Gbps (about 4.48 Tbps) along a repeaterless 302 km SSMF G.652. Using the designed amplifiers, it was possible to achieve 302 km of repeaterless transmission distance with 40 WDM channels occuping the red C-band (upper half of the C-band, from 1544.94 nm to 1560.60 nm). To enhance the bandwidth-distance product, it is necessary to redesign the amplifier topology to increase the number of transmitted channels. Work is under way to improve the amplifier design to cover the full C-band. It consists on optimizing both the transmitter and receiver hybrid optical amplifiers to provide the lowest possible noise figure together with flattened spectral gain at both hybrid amplifiers.

Specifically, considering the hybrid amplifier as a single entity (EDFA and co-propagating DRA in the same optical circuit), it is desirable to increase the number of Raman pump lasers, and choose the pump wavelengths through a multi-parameter optimization method, aiming a flat spectral gain with no use of lossy passive components, such as GFFs. This could optimize the OSNR along the full C-band, as long as the power onset for non-linearities (the combined co-propagating pump power plus EDFA signal output and the counter-propagating pump power must stay below the maximum G.652 power limit) is avoided.

It is worth mentioning that [11], reports a slightly longer span distance, albeit presenting a smaller number of channels (eight against forty) than in our case. However, achieving this longer distance required four Raman pump lasers, 20% overhead FEC (software and hardware defined FEC) and in-line CD compensation. On the other hand, [21] clearly shows that 100 G WDM systems which carry out CD compensation through DSP (instead of using optical DCM modules), suffer from less significant non-linear effects. This is why our transmission strategy, using DSP CD compensation, cheaper Raman amplifiers (only two pumps for both co- and couter-propagating DRA) and raising the lauch power to operate near but below the 7% overhead pre-FEC (hardware defined FEC) threshold, allowed almost the same repeaterless span length, with a larger number of channels.

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Juliano Rodrigues Fernandes de Oliveira was born in Nilópolis, Brazil in 1982. He received the degree in electrical engineering from Federal University of Campina Grande (UFCG) 2005 and M.Sc. Degree in Electrical Engineering from Campinas State University (UNICAMP) 2008 and is concluding his Ph.D. at São Paulo University (USP/EESC).

He participate out of 8 research and development projects in optical communications at CPqD Foundation, leading 2 projects, producing 3 patents (INPI), and 20 publications between journals and conferences. Today he is leading research and development projects at optical communications sub-systems at CPqD Foundation, with emphasis in Optical amplifiers (EDFA and Raman), ROADMs and reconfigurable/autonomous optical networks.

Uiara Celine de Moura was born in Cabo de Santo Agostinho, Pernambuco in 1983. She received the degree in electrical engineering from USP (University of São Paulo) in 2011. She is concluding the M.Sc. degree in electrical engineering at São Paulo University (USP/EESC).

She is a telecommunications researcher at CPqD since 2011. She works at the high performance optical amplifier design and in autonomous optical networks.

Getúlio Eduardo Rodrigues de Paiva was born in Uberlândia, Brazil in 1986. He holds M.Sc. (USP–University of Sao Paulo, 2012) and bachelor’s (UFScar – Federal University of Sao Carlos, 2008) degrees in Telecommunications and Physics, respectively.

He is a telecommunications researcher at CPqD since 2010 and, since 2009, is working with high performance optical amplifiers (EDFA and Raman) and their applications.

Alexandre Passos de Freitas was born in Campinas, Brazil in 1986. He received the degree in electrical engineering from Campinas State University (Unicamp) in 2011.

He is a researcher at CPqD since 2011. He is currently working on optical amplifiers design and fabrication of integrated photonic components.

Luis Henrique Hecker de Carvalho was born in Campina Grande, Brazil in 1988. He received the degree in electrical engineering from UFCG (Campina Grande Federal University) in 2011.

He is a researcher at CPqD since 2011. He is currently working on advanced modulation formats research for signals transmission and reception over WDM optical networks.

Victor Emanuel Parahyba was born in Fortaleza, Brazil in 1988. He received the degree in electrical engineering from Campinas State University (Unicamp) in 2011.

He is a researcher at CPqD since 2011. He is currently working on non-linear compensation DSP algorithms research for advanced modulation formats signals transmission and reception over WDM optical networks.

Júlio César Rodrigues Fernandes de Oliveira was born in Campina Grande, Paraíba in 1980. He received the electrical engineering degree from Federal University of Campina Grande (UFCG) 2003, M.S. and Ph.D. in from Campinas State University (UNICAMP) in 2004 and 2007, respectively.

He is now the manager and research leader at optical communications systems and sub-systems area at CPqD Foundation. He has lead 10 optical communications R&D projects, producing 5 patents (INPI), 15 journals articles, 57 proceedings papers in conferences and 5 technological products to the brazilian optical communications industry. His research interest topics are related to optical communications regarding to high speed optical transmission (100 Gb/s) and reconfigurable optical networks, among them, optical amplification, optical monitoring, ROADMs, GMPLS control plane, among others.

Murilo Araujo Romero was born in Rio de Janeiro, Brazil, in 1965. He received the electrical engineering and the M.S. degrees in 1988 and 1991, both from the Catholic University of Rio de Janeiro, Brazil. In 1995, he received the Ph.D. degree from Drexel University, Philadelphia, USA. His thesis work dealt with optically controlled microwave devices and high-speed photodetectors for optically feed phased array antennas. After his return to Brazil in 1995, he joined the University of Sao Paulo, at Sao Carlos, as a faculty member. At the University of Sao Paulo (USP), he became an Associate Professor in 2001 and a Full Professor in 2008.

He is now the Head of the Electrical Engineering Department at EESC-USP and Chair of the Electrical and Biomedical Engineering Committee of the Brazilian Research Council (CNPq). His research interests span over a large variety of topics in the microwave-photonics area, including microwave semiconductor devices and circuits, optical amplifiers, optical fibers, and optical networks. Samples of his research work can be found in 43 journal papers, including manuscripts at IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS, IEEE TRANSACTIONS ON ELECTRON DEVICES, IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE Sensors, Electronics Letters, Applied Optics and Optics Express, among other journals.