

Transmission of a 20 Gb/s NRZ OOK Signal Throughout a 390 km Fiber Link and a Cascade of 11 x 50 GHz Filters and 9 x EDFAs

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Abstract— This paper presents a qualitative analysis of the impact caused by fiber propagation effects and by a cascade of optical filters, designed for 10 Gb/s NRZ OOK transmission, and optical amplifiers on a 20 Gb/s NRZ OOK optical signal traveling a 390 km fiber link. The choice for such bit rate and modulation format has been driven by the 50 GHz bandwidth of the filters (in the ITU DWDM grid) and by simplicity and low cost, respectively. The system, investigated experimentally and numerically, comprises 4 spans of standard fiber and a concatenation of 7 dispersion compensating modules, 4 wavelength selective switch reconfigurable optical add and drop multiplexers, 9 erbium-doped fiber amplifiers and 1 WDM-DEMUX (> 75 GHz bandwidth). We demonstrate the feasibility of such bit rate upgrade in a cost-effective network planning strategy, which may be more adequate for regions where the demand for bandwidth do not require a jump to higher capacities (i.e. 40 and 100 Gb/s), thus allowing for reusing the 10 Gb/s installed infrastructure.

Index Terms— Amplified spontaneous emission accumulation, fiber propagation effects, dispersion compensating module, non-return-to-zero on-off key 20 Gb/s, spectral narrowing, wavelength selective switch reconfigurable optical add and drop multiplexer.

I. INTRODUCTION

Nowadays, the majority of optical networks in operation have been designed and optimized for transmission of 10 Gb/s Non-Return to Zero (NRZ) ON-OFF Keying (OOK) in a Dense Wavelength Division Multiplexing (DWDM) system. As the Internet traffic increases, higher bit rates are required for supporting the bandwidth demand, which leads to the recursive problem of fulfilling the capacity requirements with a minimum capital expense [1]. In this scenario, a key design driver is that the new systems must ideally integrate with the existing ones without requiring significant changes to the installed equipment. Many technologies have been considered for the next bit rate hierarchies, i.e. 40 Gb/s, 100 Gb/s and beyond, most of them based on phase modulation techniques and coherent

detection, which present higher spectral efficiency and may be less affected by linear regime physical impairments [2], [3]. However, phase modulation and coherent detection not necessarily lead to higher spectral efficiency. This happens only if such modulation techniques are associated with multi-level signaling. Such higher bit rates imply that the emerging technologies must support a wide bandwidth signal [2]. Under such spectral constrain, the low cost requirement is not well accomplished since part of the network legacy may not be used, added to the fact that those solutions are expensive and technically complex [4].

Considering propagation in linear regime, some of critical parameters to overcome are chromatic dispersion, Polarization Mode Dispersion (PMD), spectral narrowing, caused by filter concatenation, and accumulated Amplified Spontaneous Emission (ASE) noise. Transmission through a cascade of optical filters, such as Dispersion Compensation Modules (DCMs), based on chirped fiber Bragg gratings, and Reconfigurable Optical Add and Drop Multiplexers (ROADMs) is common place in Metro and Long-Haul networks. Particularly for 40 Gb/s, it may be a more severe impairment than for 100 Gb/s, where the modulated signal results from the multiplexing of 4 x 25 Gb/s streams, as recommended by the Optical Internetworking Forum (OIF) for coherent Dual Polarization Quadrature Phase Shift Keying (DP QPSK) [5]. Furthermore, despite the advantages provided by the new formats and technologies, traffic demands across the network may not require 40 and 100 Gb/s capacity everywhere. So, a cost-effective network design needs to exploit the scenario of operation with Mixed Line Rates (MLRs) [1], [6].

In that approach, we have investigated the possibility of implementing an intermediate upgrade in an existing 10 Gb/s infrastructure without much expenses, by using NRZ OOK, direct detection and low loss optical dispersion compensator, i.e. 10 Gb/s-designed DCM based on chirped gratings, thus allowing for propagation in linear regime. We then analyze the effect of a large concatenation of filter and ASE across a nearly 400 km long optical path traversed by a 20 Gb/s NRZ OOK signal. That bit rate has been chosen due to the 50 GHz bandwidth of each filter, which does not allow the transmission of a 40 Gb/s NRZ OOK signal. We have carried out experimental and numerical measurements for evaluating the transmission performance.

The paper is organized as follows. Section II presents the implications of optical filters concatenation, Section III describes the experimental setup and the numerical simulation parameters. Section IV presents the results and discussion and, in Section V, the conclusions are described.

II. CASCADE OF OPTICAL FILTERS

In a WDM optical network, a signal can be filtered several times from its origin to its destination. That filtering comes from the signal passage, for example, through ROADMs, DCMs and Optical Cross-Connects (OXC), which may be installed along the optical path. Those filters exhibit nonideal transfer functions for optical amplitude and phase, which causes passband curvature in their frequency

response, tilt and ripple. Moreover, the phase transfer function can not vary linearly with frequency. Those effects are magnified by increasing the concatenation of devices, thus causing spectral clipping of the signal spectrum and/or dispersion problems due to nonlinearities of the phase response, which can limit the maximum link length [7], [8].

The spectral clipping and dispersion of the filter can lead to the signal distortion in the time domain, causing a *Q*-factor penalty. The effective spectral transfer function of a cascade of filters results from the multiplication of all filter responses and, generally, is much narrower than that due to a single filter. Figure 1 shows the effective transfer functions of a single optical filter with 36 GHz bandwidth and 12 cascaded and aligned filters, obtained with the Optiwave Systems Inc. OptiSystem 9.0 software tool. As expected, it can be noticed that the effective filter function after 12 filters is much narrower than after a single filter.

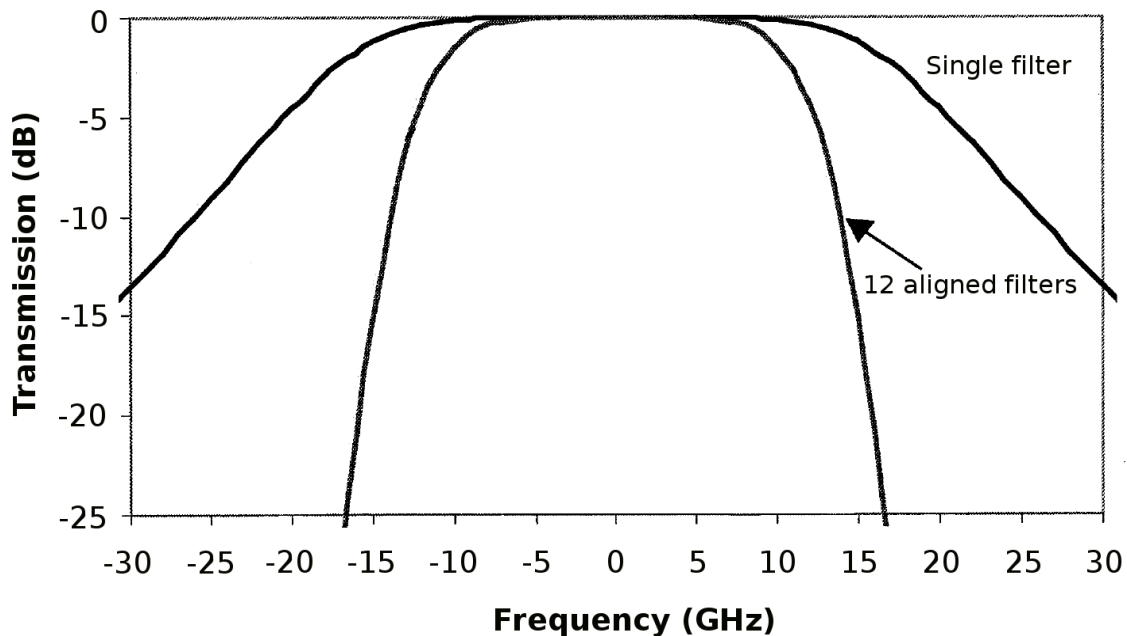


Fig. 1. Effective transfer functions of a single optical filter and 12 aligned filters.

The optical impairment penalty associated with filter concatenation effects is define as an eye-closure penalty (ECP). For a thermal noise-limited system, the eye-closure penalty may be further translated into a *Q*-factor penalty. The ECP calculation considering only contributions to the eye closure from signal distortion can be obtained as:

$$ECP = 20 \log \left[\frac{(I_{1,min, BB} - I_{0,max, BB}) / I_{ave, BB}}{(I_{1,min} - I_{0,max}) / I_{ave}} \right] \tag{1}$$

where the numerator represents the eye opening in the back-to-back condition and the denominator represents the eye opening under the fiber transmission conditions [9]. Note that the ECP in decibel is defined in the $20 \log ()$ format, here, but may be estimated in the $10 \log ()$ format in case the intensity *I* has been given in power unit. In equation (1), $I_{1,min, BB}$ and $I_{1,min}$, correspond to the minimum

value of level '1', in the back-to-back and fiber transmission configurations, respectively. Similarly, $I_{0,max, BB}$ and $I_{0,max}$, to the maximum value of level '0', in the back-to-back and fiber transmission configurations, respectively and, finally, $I_{ave, BB}$ and I_{ave} correspond to the eye-diagram average intensity in the back-to-back and fiber transmission configurations, respectively.

III. SETUP

A. Experiment

Figure 2 shows the experimental setup. The pilot signal, generated by a CW external cavity laser, operates in a constant power mode and is tuned into $\lambda = 1544.53$ nm, channel 41 of ITU DWDM grid. The laser output is connected to a lithium niobate Mach-Zehnder modulator, designed for 40 Gb/s through a polarization controller, which provides the modulator extinction ratio optimization. External 20 Gb/s RF signal, coming from a NRZ $2^{31} - 1$ Pseudo-Random Bit Sequence (PRBS), and amplified by a broadband (40 GHz) amplifier, is injected into the RF input of the modulator. Four WSS-based ROADM units, designed and developed at CPqD, Brazil, are placed, each one in-between two erbium-doped fiber amplifiers, where the first one operates as an insertion loss compensator (pre-amplifier) and the second boosts the signal at each span input. Four singlemode standard fiber (G.652) links complete the propagation medium (3 x 100 km and 90 km), leading to a total of 390 km transmission length.

Seven DCMs with fixed and tunable dispersion, based on chirped fiber Bragg gratings, are placed at the output of the spans, according to the following scheme: DCM1 comprises one fixed dispersion module (for 80 km, i.e. -1340 ps/nm), which means that a residual dispersion is added into the second span; DCM2 corresponds to the combination of one fixed (80 km, -1340 ps/nm) and one tunable (set to -550 ps/nm) compensator; DCM3, two fixed modules (60 km, -1005 ps/nm, and 40 km, -670 ps/nm); DCM3, two fixed (60 km, -1005 ps/nm, and 40 km, -670 ps/nm); DCM4, one fixed (60 km, -1005 ps/nm) and one tunable (set to -350 ps/nm). At the link end, another pre-amplifier is used to improve the receiver sensitivity, furthermore, an extra WDM-DEMUX (>75 GHz bandwidth) is used to select the transmitted channel (Ch 41) and also to filter the ASE coming from that EDFA. For performance monitoring, we use a wideband scope, synchronized by a clock recover equipment and an Optical Spectrum Analyzer (OSA). For visualizing the eye diagrams, from which we qualitatively evaluate the transmission performance throughout the line, we use a plug-in converter, which provides singlemode optical channel unfiltered Bandwidth (BW) of 40 GHz, with optical transition time ($= 0.48 \times BW^{-1}$) of 12 ps at Full Width Half Maximum (FWHM) and 65 μ W of characteristic RMS noise. For the electrical side, this module provides 50 GHz BW, less than 13.2 ps of transition time ($= 0.35 \times BW^{-1}$) and 0.60 mV of characteristic RMS noise. Note that the high electrical bandwidth of the photodiode is expected to produce, as a drawback, a large amount of electrical noise. As the photo-detector saturation could cause nonlinear distortions, which could limit

the dynamic range of the link, in our setup the front end is protected by an optical monitor/attenuator, which limits the maximum optical power incident on it.

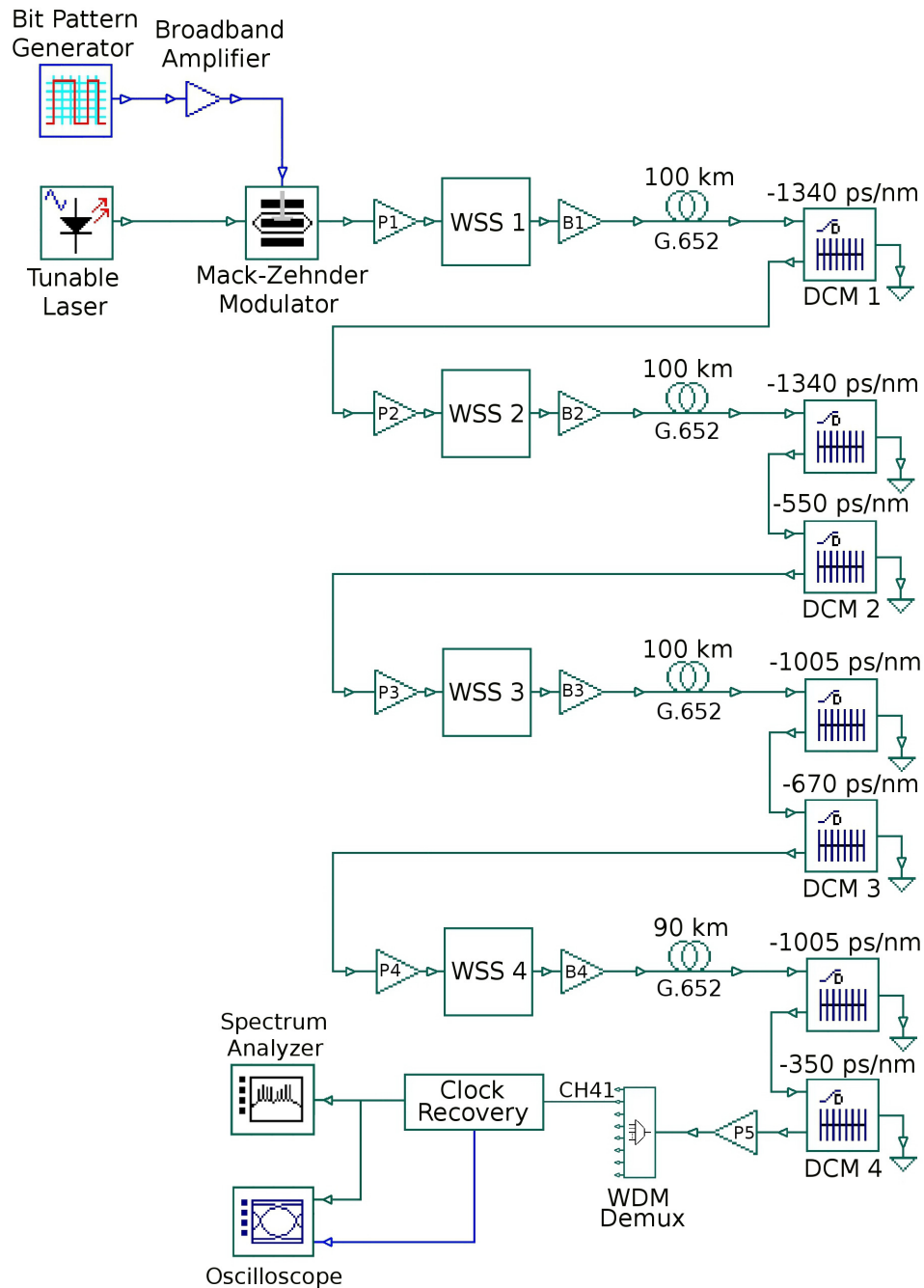


Fig. 2. Experimental setup. P_n, WSS_n and B_n stand for the n-th Pre-amplifier, Wavelength Selective Switch and Booster amplifier, respectively. G.652 refers to the ITU recommendation relative to the standard singlemode fiber. DCM stands for Dispersion Compensating Module.

B. Simulation

We used the same experimental diagram in the OptiSystem 9.0 simulator, that solves the nonlinear Schrödinger equation, configured with the parameters indicated in Table 1. Some parameters, such as responsivity, thermal noise and dark current are not available, and have been set to default values.

TABLE I. SIMULATION PARAMETERS (SAME USED IN THE EXPERIMENTAL SETUP)

	Parameter	Unit	Value
SML (single mode laser) (External cavity laser)	Linewidth	MHz	0.2
	Wavelength	nm	1544.53
	Output power	dBm	11
Line code		-	NRZ
Bit rate			40 and 20 Gb/s
Modulator insertion loss		dB	12
EDFA (Erbium-doped fiber amplifier)	Gain P1	dB	10
	Gain B1	dB	16
	Gain P2, P3, P4, B2, B3 and B4	dB	22
	Gain P5	dB	10
	Noise Figure (all amplifiers)	dB	5
Fiber SMF-28 (singlemode fiber) (ITU-T recommendation G.652)	Attenuation	dB/km	0.2
	PMD	ps.km ^{-1/2}	0.5
	Chromatic dispersion	ps/nm.km	16.75
	Dispersion slope	ps/nm ² .km	75
Effective area	μm ²	80	

IV. RESULTS AND DISCUSSION

In order to evaluate the physical impairments on a 40 Gb/s NRZ OOK signal, we simulated its transmission on the setup seen in Figure 2. The eye diagrams, presented in Figure 3, confirm the strong limitation imposed by the impairments on that bit rate and modulation format propagation.

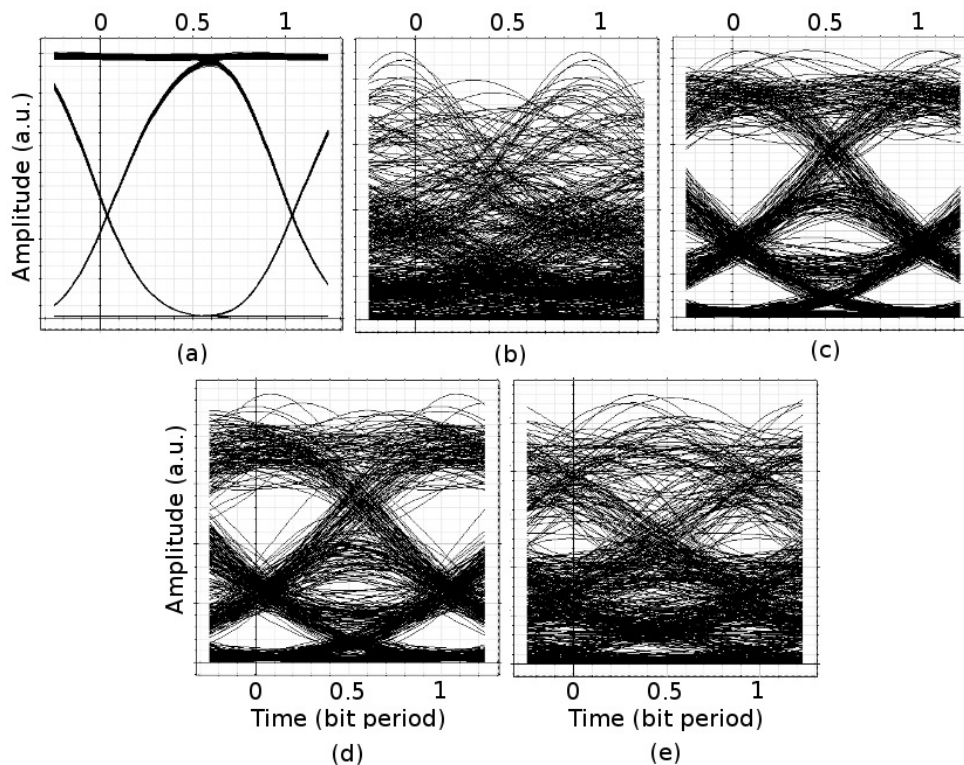


Fig. 3. 40 Gb/s simulated eye diagrams seen at: (a) back to back configuration; (b) after DCM1; (c) DCM2; (d) DCM3; and (e) DCM4.

The eye diagram degradation is a consequence of many effects in mutual combination, but by observing the spectral narrowing due to the cascade of filters (WSSs, DCMs and DEMUX) 3 along the optical path, as indicated in Figure 4, it is possible to infer how strongly the narrow spectral window might penalize the system performance. This fact, alone, implies that for such system configuration, the transmission of 40 Gb/s NRZ OOK is not feasible, despite of other problems associated to other physical impairments. From those indications, and considering the aim of reusing a 10 Gb/s infrastructure, we have chosen 20 Gb/s NRZ OOK as the basis for our investigations. Therefore, from then on, the results are referred to it.

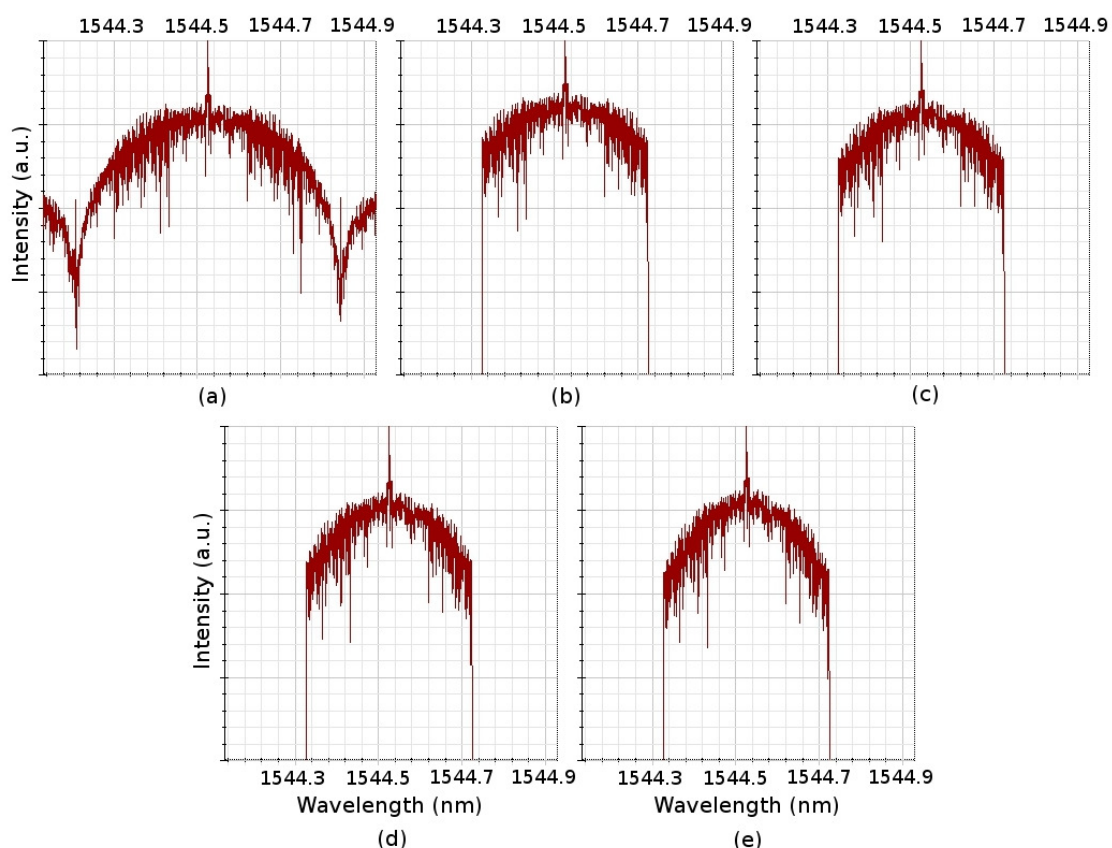


Fig. 4. 40 Gb/s simulated spectra seen at: (a) back to back configuration; (b) after DCM1; (c) DCM2; (d) DCM3; and (e) DCM4.

The 20 Gb/s eye-diagrams, for the simulation and experiment, are shown in Figures 5 and 6, respectively. As the first dispersion compensation stage, DCM1, does not match the required dispersion value, the performance degradation due to residual dispersion is notable. However, we observe an improvement in performance after DCM2, that also compensated the residual dispersion, and a more natural degradation from then on, due to the other impairments. Three of them, ASE accumulation, electrical noise (the front end bandwidth, 40 GHz, is higher than necessary) and PMD were expected. One must notice that the deleterious effects associated to PMD have not been combated in any way.

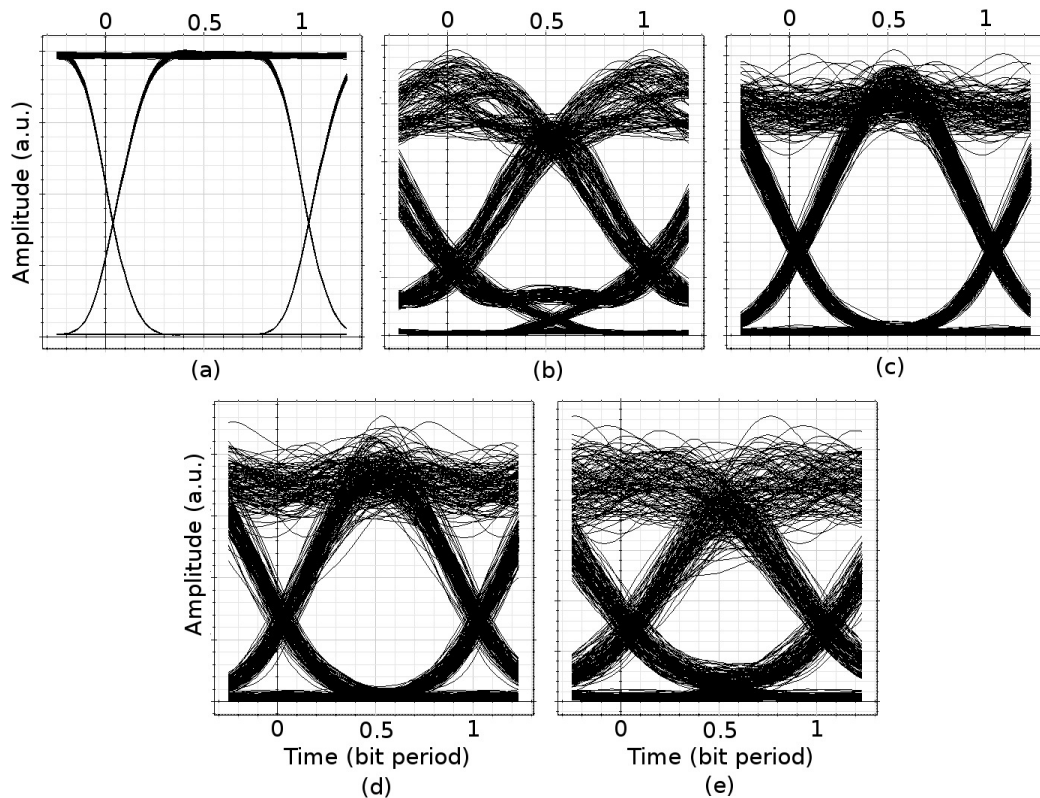


Fig. 5. 20 Gb/s simulated eye diagrams seen at: (a) back to back configuration; (b) after DCM1; (c) DCM2; (d) DCM3; and (e) DCM4.

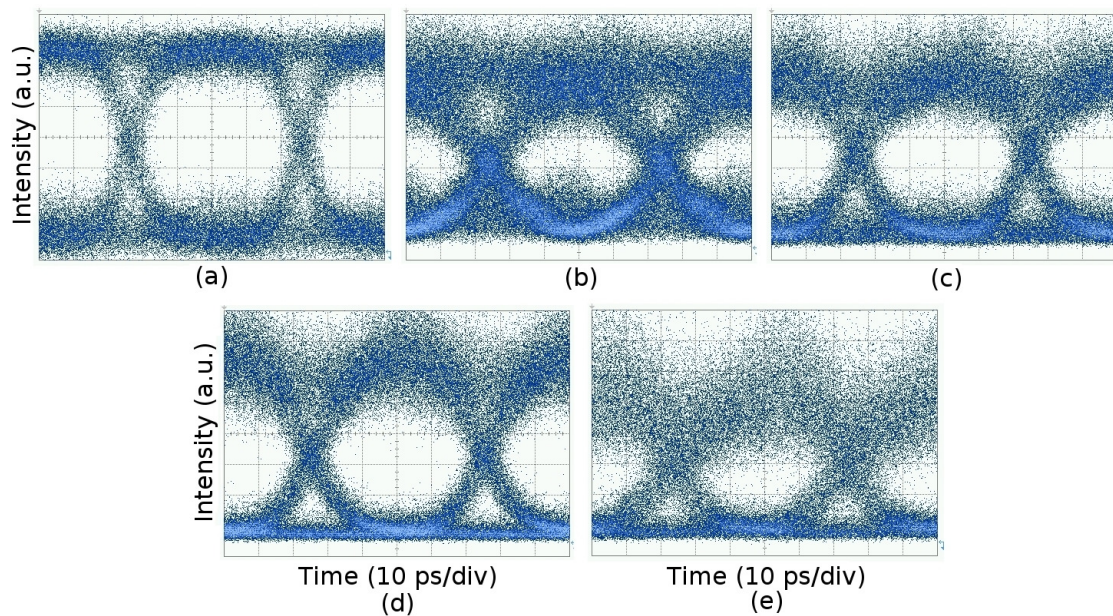


Fig. 6. 20 Gb/s Experimental eye diagrams (horizontal scale of 10 ps/div, for each graph) seen at: (a) back to back configuration; (b) after DCM1; (c) DCM2; (d) DCM3; and (e) DCM4.

For evaluating the filter concatenation influence, we have carried out spectral simulations and measurements, which are summarized in Figures 7 and 8, respectively. From Figure 7 we notice a loss of side lobe with spectral narrowing after propagation throughout the filters, which lead to the

conclusion that even at 20 Gb/s the cascade of seven 50 GHz filters represent a limitation for the system performance.

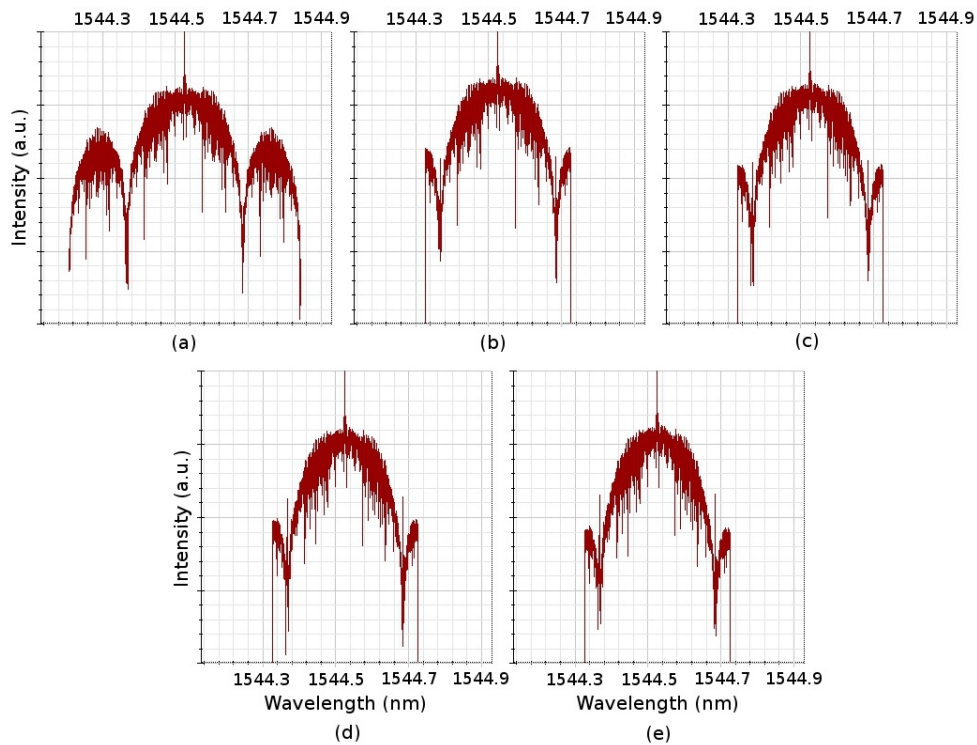


Fig. 7. 20 Gb/s simulated spectra seen at: (a) back to back configuration; (b) after DCM1; (c) DCM2; (d) DCM3; and (e) DCM4.

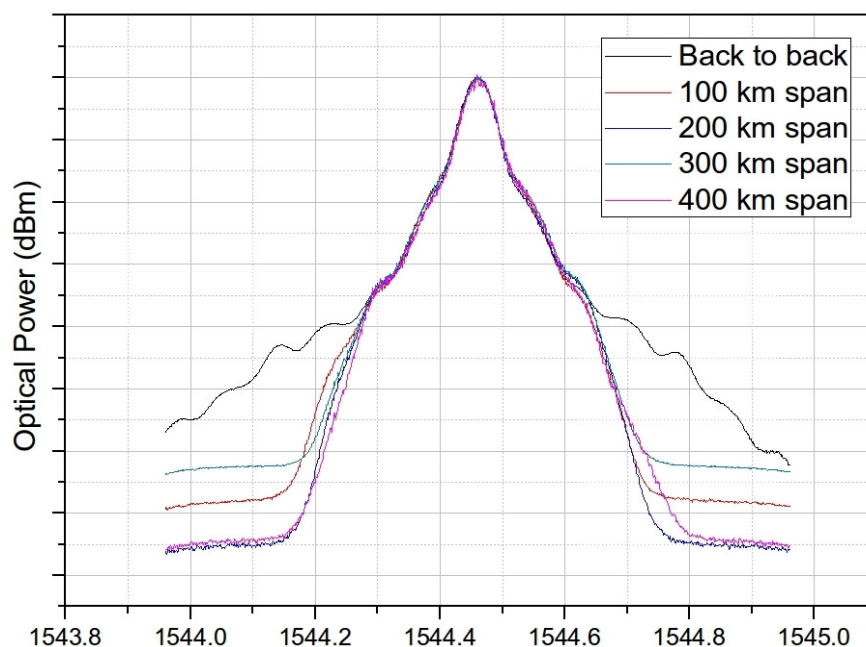


Fig. 8. Experimental optical spectrum of the 20 Gb/s signal in the back-to-back configuration and at the end of each fiber span (5 dB/div).

We also notice, in the experimental data, that the spectral narrowing may be slightly observed with an alignment, in amplitude, of the curves, thus highlighting the similarity between the spectra that

cross the filters and the one that does not cross them (the back to back transmission). Furthermore, for the ASE accumulation effect, the modulated signal spectra after the 390 km path does not show a significant Optical Signal-to-Noise Ratio (OSNR) penalty (OSNR \approx 15 dB). One should note that the excess of filtering along the optical path, if by one side limits the overall bandwidth, by the other side acts to reduce the impact caused by ASE concatenation due a cascade of optical amplifiers, which has been confirmed by our results.

Finally, we should remember the extra electrical bandwidth of the optical receiver, designed for 40 Gb/s measurements, which is likely to add extra electrical noise to the measured eye diagrams seen in Figure 7. Considering that, it is reasonable to expect that a receiver designed for 20 Gb/s would allow the reception of cleaner eye diagrams. Other effects, besides ASE accumulation, electrical noise and PMD, such as nonlinear effects, could be further investigated in configurations with higher optical power levels. For those used in the setup, we have not observed any strong impact caused by fiber nonlinearities.

By using Equation (1) in the eye diagrams corresponding to the back-to-back and 390 km transmission configurations, we have estimated the experimental and simulated eye-closure penalties (ECP) as being around 1.1 dB and 0.8 dB, respectively. The ECP evaluation caused by filter concatenation, for transmission rates varying from 2,5 to 100 Gb/s in different modulation formats, has been studied by many authors [10]-[13]. One must remember that not only the cascade of filters plays a role on the final penalty but it is combined with other degrading effect such as group delay ripple and spectral misalignment caused by detuning of either, the WSSs, the laser source, or both.

For future reconfigurable networks, the ability to transmit through multiple 50 GHz reconfigurable optical add/drop modules is becoming increasingly important yet challenging, which has motivated us for evaluating a higher data rate (20 Gb/s) single-channel transmission through a setup configured for transmitting multiple 10 Gb/s channels. Further studies with WDM transmission should, then, considered the contribution of other associated constraining effects, such as signal cross talk caused by leakage from adjacent channels.

Although a study made with the help of the bit error rate (BER) parameter would give us a quantitative idea of the penalty caused by the group of deleterious effects, we believe that each effect should be studied in an isolated configuration, first, in order to give us a better idea of its contribution to the total penalty, which is the subject of future investigations

V. CONCLUSION

The transmission through nearly 400 km-long singlemode fiber of a NRZ OOK signal modulated at 20 Gb/s has been demonstrated. Although evaluated as a point-to-point link, the optical path comprises four nodes with ROADMs designed for a DWDM network operation. According to the results, we observe that the presence of accumulated effects, that would not allow the transmission of a 40 Gb/s NRZ OOK optical signal, have not severely impacted the 20 Gb/s transmission throughout a

large amount of filters (4 x WSS ROADMs, 7 x DCMs) and EDFAs (9 units). By contrary, considering the possibility of including some forward error corrector technique, which could improve the system performance, it is reasonable to affirm that the use of 20 Gb/s NRZ OOK may be a cost effective strategy for network upgrades where the increase in capacity does not require a jump to higher bit rates, which would imply in more complex and expensive technologies, such as coherent detection with phase modulation formats. This way, the legacy of 10 Gb/s systems could be preserved and reused, in a good choice for the network planning made by carriers that aim to keep in balance the Capex.

Finally, one should notice that bit rates of 10, 40 and 100 Gb/s are standardized in Telecommunications industry and the analysis presented in the paper is performed in a system with 20 Gb/s which is not a standard bit rate. However, the use of 20 Gb/s has increased in recent years, mainly due to applications where modulation formats such DQPSK (and OFDM (Orthogonal Frequency Division Multiplexing) are employed [14], [15].

ACKNOWLEDGMENT

This work has been supported by Funttel (Finep) and Fapesp (grant 06-04546-4).

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