System performance evaluation of an optical superchannel originated from different optical comb generation techniques

Rafael Jales Lima Ferreira, Mônica de Lacerda Rocha,
Electrical Engineering Department, Engineering School of São Carlos, University of São Paulo
SEL-EESC USP, São Carlos, Brazil rafael_jales@hotmail.com, monica.rocha@usp.br
Stenio Magalhães Ranzini
Research and Development on Telecommunication Center Foundation,
CPqD, Campinas, Brazil, stenio@cpqd.com.br

***Abstract*—We describe three optical comb generation techniques to be used as part of ultra-high bit rate (i.e. above Tb/s) systems: (i) recirculating frequency shifting, (ii) cascade of optical modulators, and (iii) laser gain switching. The comb generators were evaluated in two different scenarios for transmitting a 10-subcarrier superchannel (10 x 112 Gb/s): (i) spectral narrowing due to filter concatenation and (ii) OSNR and signal degradation due to ASE accumulation and standard fiber propagation effects. By using a coherent receiver and offline digital signal processing, the techniques were compared in terms of bit error rate performance.**

***Index Terms*— Optical comb generation, optical superchannel, recirculating frequency shifting, cascade of optical modulators, laser gain switching, coherent detection.**

I. INTRODUCTION

As pointed out by most data traffic forecasts, the next generation optical transmission systems are expected to operate at bit rates exceeding 100 Gb/s/channel [1]. For achieving such target, one of the most promising solutions is based on the association between optical combs and special modulation schemes in a way to provide a set of mutually orthogonal optical signals that will be transmitted with coherent detection. Those multicarrier schemes usually do not require the use of guard bands between channels and, with special modulation formats, make more efficient use of the available optical bandwidth. One of the techniques that enable transmission of several Tb/s per fiber relies upon the use of coherent and orthogonal multi-carriers (CO-OFDM, coherent orthogonal frequency division multiplexing) originated from a single laser source, thus resulting in a high aggregate capacity and spectral efficiency techniques that exploits parallel processing with moderate bit rate per carrier. Such optical signal, produced from a single laser, comprises multiple orthogonal carriers locked in frequency and synchronously modulated and is usually called *superchannel* [2].

Despite of its attractive features, the superchannel solution still presents challenges with a considerable high level of complexity. In order to achieve the targets described above, one has to make sure that some conditions are met before a single channel, among several others, can be detected with minimum penalty caused by interference between channels and symbols. In fact, at least the

 received 29 March 2013; for review 9 May 2012; accepted 1 Aug 2013
  ISSN 2179-1074

following requirements should be fulfilled [3]:

(i) carrier separation is equal to the symbol rate of each modulated carrier;

(ii) symbols, in modulated carriers, are aligned in time;

(iii) the transmitter bandwidth is large enough to accommodate the carriers; and

(iv) appropriate sample rate and anti-aliasing filtering are applied.

An important feature of the superchannel signal is that the bigger the number of subcarriers the smaller should be both the difference between their frequency separation and the symbol transmission rate of each subcarrier. Therefore, it is crucial to generate stable subcarriers, without variation both on their frequency interval and on the transmission rate.

A typical superchannel transmitter is illustrated in Fig. 1, where the modulated signal is generated from a seed laser incident on an optical comb generator (OCG) block. Alternatively, instead of being a process external to the laser, the OCG process may occur inside the cavity laser, as it will be illustrated later.

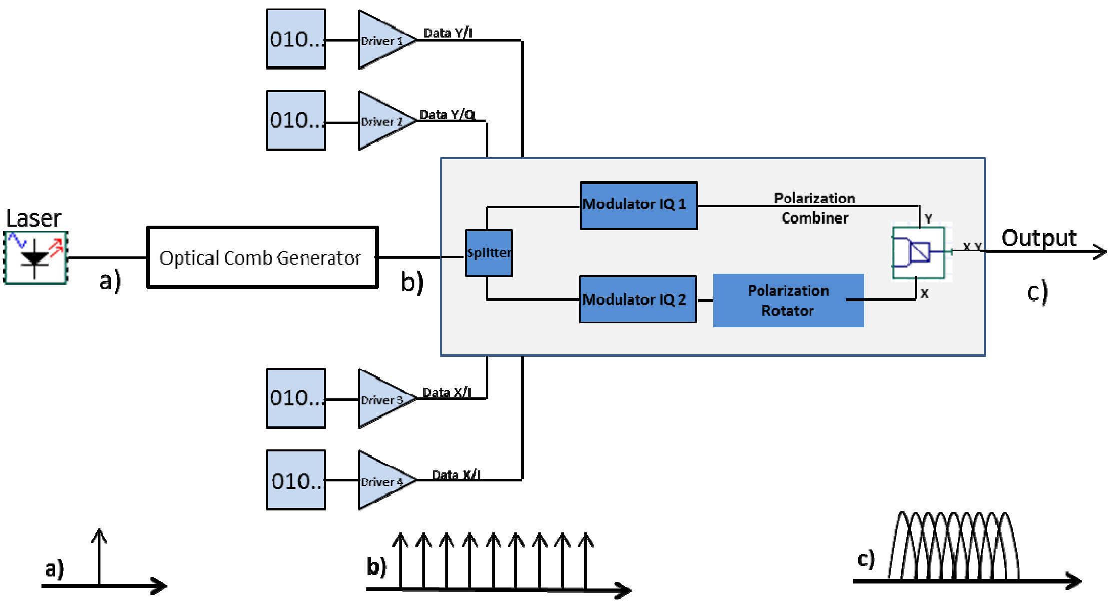


Fig. 1. Superchannel, with frequency locked subcarriers, transmitter.

As indicated in Fig. 1, after the comb generation, the next step is the modulation of each subcarrier (also named optical channel). In the example, a dual polarization quadrature phase-shift keying (DP-QPSK) modulation scheme has been employed. At this stage, to fulfill the mutually orthogonal subcarriers condition, the modulated comb lines should be spaced by a value that is equal to the symbol rate. For instance, they should be spaced in intervals of 25 GHz if modulated at 25 Gsymbols/s, each. Once the orthogonality is achieved, the need for a guard band interval between adjacent subcarriers becomes dispensable. At the modulator output the superchannel is, then, ready to be transmitted.

In this paper, we present a study of three techniques for generating optical comb lines which can be used, in association with special modulation formats, in transmitters and receivers of ultra-high capacity systems. By using a commercial optical system simulator (Optsystem) [4], the following techniques will be described and compared:

(i) Cascade of Mach-Zehnder Modulators (MZM) or of Phase Modulators (PM) - commonly used to generate signals around two to eleven carriers; its limitation is the number of generated subcarriers, which is determined by the modulators' bandwidth and by the maximum amplitude of their driver signals [5];

(ii) Recirculating Frequency Shifting, RFS - based on the frequency conversion produced by single side band modulation, allows the generation of great number of highly stable carriers [6]; and

(iii) Gain switching in semiconductor lasers driven by an intense sine wave –similar to the Discrete mode laser (DM) technique, resulting in phase locking of the comb line at the laser output. Its main advantages are simplicity and low cost [7].

The paper is organized as follows. Sections II, III and IV describe each technique principle; section V presents the simulated results in a comparison between the techniques for two recirculating loop transmission setups that will stress the spectral narrowing, due to an optical filter concatenation, and amplifier stimulated noise (ASE) accumulation and linear fiber propagation effects; finally, sections VI and VII discusses the results and presents some conclusions, respectively.

II. Cascade of Modulators

In this approach, two or more cascaded modulators are driven by phase-controlled sinusoidal electrical waves (at same RF frequencies). It is important to notice that not just MZ modulators may be cascaded, the setup may comprise a cascade of phase modulators (PM), or a combination of PMs and MZs. The important point here is that each modulator will produce a set of side bands shifted by the RF frequency applied on the modulators. Another important aspect is that, in order to keep the overall optical to signal to noise ratio (OSNR) equalized, the amplitude of each subcarrier will have to be individually controlled. Figure 2 illustrates the simulation pallet for this OCG, although it does not indicates the scheme employed for the signal equalization. In our tests, an optical comb with 10 lines has been generated by two cascaded MZs (later on replaced by two PMs). For the equalization process, it is sliced by a WDM demultiplexer, which allows the use of variable optical attenuators (VOAs) that will adjust the amplitude of each channel. Once the comb spectrum becomes flat, the subcarriers are individually modulated and recombined by a WDM multiplexer.

  ISSN 2179-1074

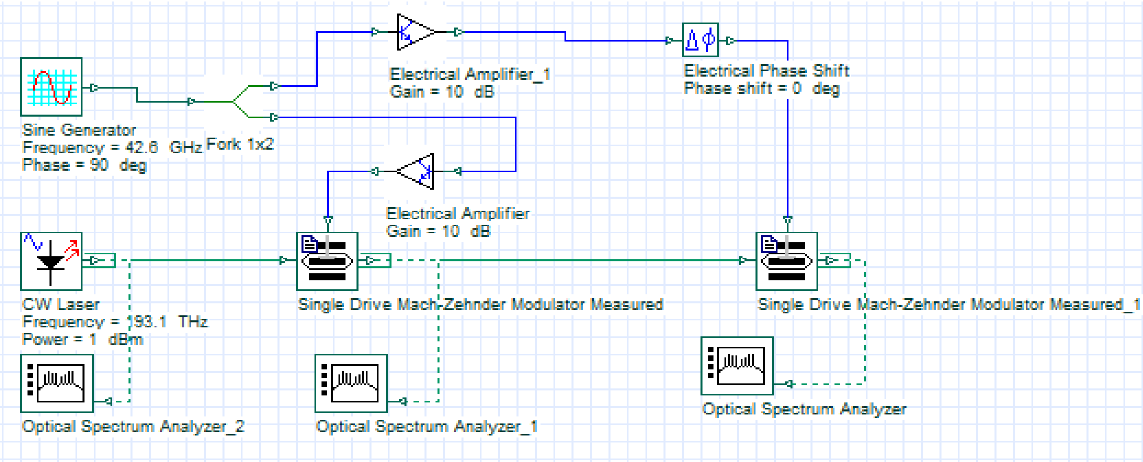


Fig. 2. Simulation pallet for the modulator cascade technique.

Figure 3 shows the optical spectrum of 10 comb lines, resultant from this 2-MZ cascade, before the modulation has been applied to the comb. The spectrum resultant from a 2-PM cascade is similar to this one.

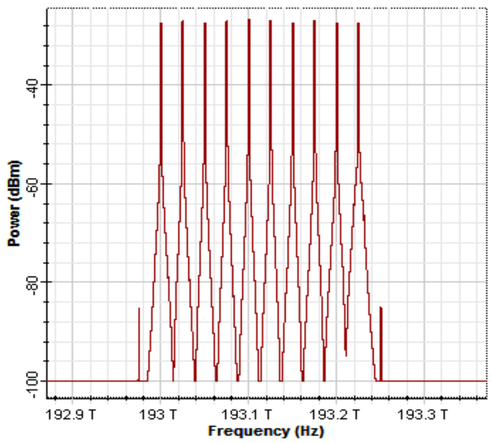


Fig. 3. Optical comb comprising 10 subcarriers, spaced by 25 GHz, generated by the cascade of 2-MZ modulators.

III. RECIRCULATING FREQUENCY SHIFTING, RFS

In the RFS technique, a cw laser signal is shifted, in frequency, within a recirculation loop due to an analog modulation process. In the configuration of our analysis (Fig. 4), the OCG consists of a seed laser, a 2 x 2 optical coupler, a double MZ modulator (QPSK MZ module, in our case, because the results were validated by an experiment that employed this type of modulator [8]), an optical amplifier (Erbium-doped fiber amplifier, EDFA), to compensate for the loop losses, and an optical filter, for limiting the number of generated subcarriers and the level of amplified spontaneous emission noise (ASE) within the loop. As indicated in Fig. 4, the cw optical signal is continuously injected into the loop through one of the coupler input ports. After each round trip, part of the signal exits the loop and part returns to it.

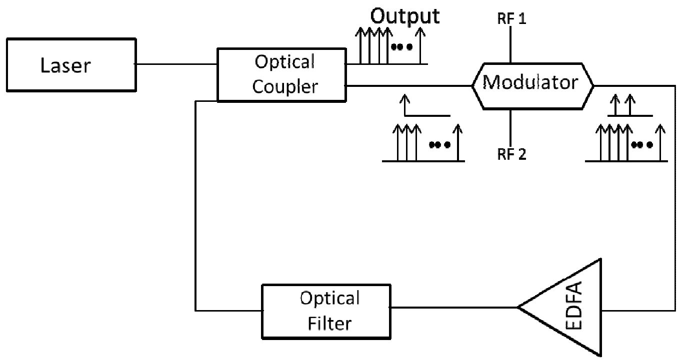
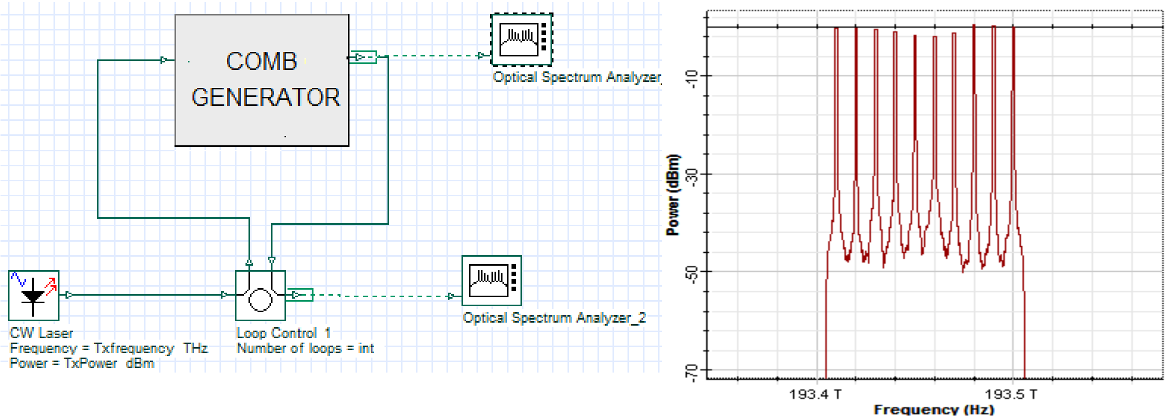


Fig. 4. Comb generator based on the recirculating frequency shifting technique.

In the loop, the modulator is electrically driven by two mutually orthogonal RF sine waves. Its biasing points are adjusted in such a way to generate a single side-band suppressed carrier (SSB-SC) signal, which is then amplified and filtered. Note that the filter output is recombined with the signal seed laser signal, at the coupler input, so that, at each round trip, new comb lines may be continuously generated while the modulator output is continuously shifted by the RF frequency applied to the modulator. After many round trips, the initial comb lines are totally shifted to outside of the filter band; however, the process assures that new comb lines will be continuously generated inside the filter band.

The simulation pallet used for this technique is shown in Fig. 5(a) and in Fig. 5(b) the optical spectrum at the OCG output is presented. Notice that, although the comb spectrum is not totally flat, the lines' OSNR vary within ± 2.5 dB, which is a reasonable range. Therefore, the VOA scheme has not been used in the RFS approach. Furthermore, the experimental setup used for the pallet calibration also does not employ any extra equalization scheme.



(a) (b)

Fig. 5. (a) Simulator pallet for the recirculating frequency shifting technique. (b) Optical spectrum of 10 comb lines, spaced by 25 GHz, for the RFS technique.

IV. Gain Switching

In this section, we describe the comb generation technique that uses a cw semiconductor laser directly modulated by an intense sine wave. It works similarly to the well-known laser gain switching [9], resulting in an optical comb with phase-synchronized lines. Compared to the previous approaches, this one is relatively simple and, consequently, of lower cost. In our implementation, the sinusoidal electrical signal was directly applied into a laser designed for direct modulation applications. Its amplitude was adjusted for OSNR values around 30 dB. The simulation pallet (without the posterior equalization and amplification scheme) is illustrated in Fig. 6, where a continuous wave laser, tuned at 1552.52 nm, is gain switched by a sinusoidal signal. Once the comb has been generated, its lines were individually equalized by a set of variable attenuators placed in between a demux and a mux. The optical comb spectrum, before the amplification and OSNR equalization stages, is seen in Fig. 7.

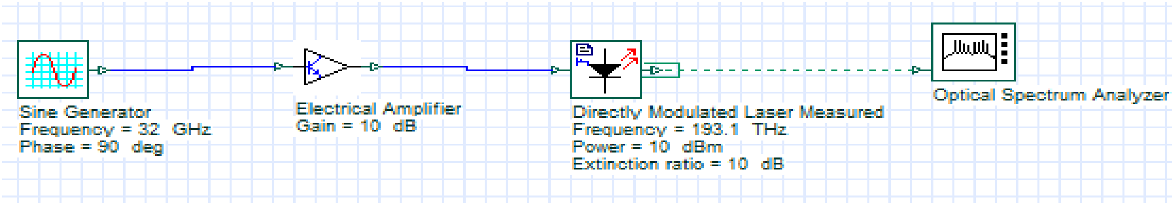


Fig. 6. Simulator pallet for the laser gain switching technique.

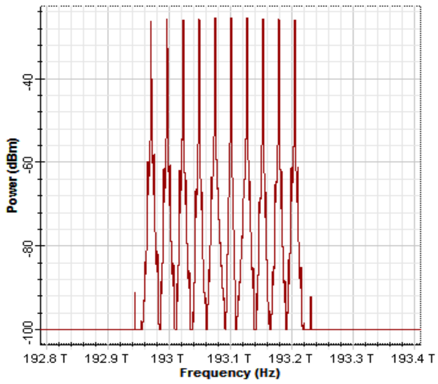


Fig. 7. Optical spectrum of 10 comb lines, spaced by 25 GHz, for the laser gain switching technique.

V. SYSTEM PERFORMANCE RESULTS

A. *Validation of the System Simulation Pallet*

Initially, to calibrate and validate the system simulation procedure, we configured a pallet with parameters and devices similar to those used in [8], an experiment that demonstrated a 452 km pure silica fiber transmission of a 10-subcarrier superchannel NGI-CO-OFDM (*no-guard-interval coherent* OFDM), modulated at net bit rate of 1.12 Tb/s. The comb lines were generated by the RFS technique, spaced by 28 GHz and modulated, each, at 112 Gb/s by a DP-QPSK (*Dual Polarization, Quadrature Phase Shift Keying*) scheme. The experiment employed a recirculating loop comprising six EDFAs and five pure silica fiber spools. A coherent optical receiver was used for recovering the amplitude and phase of the subcarriers, where the local oscillator was tuned to the channel under evaluation. A digital signal processing of the signal samples was carried out offline by a DSP module adapted for OFDM system studies. The simulation pallet and the results, for the extreme (#1 and #10) and middle channels (#5), are presented in Figs. 8 and 9, respectively. The difference between simulated and experimental results ranges within less than one magnitude order, in terms of BER, which may be

  ISSN 2179-1074

considered consistent and sufficient for carrying out the OCG techniques evaluation in different transmission configurations. Those differences may be due to experimental spurious effects, such as laser phase noise and frequency offset, not exactly matched in the simulations. This analysis took into account a Forward Error Corrector (FEC) limit of 3.8 x 10^{-3}.

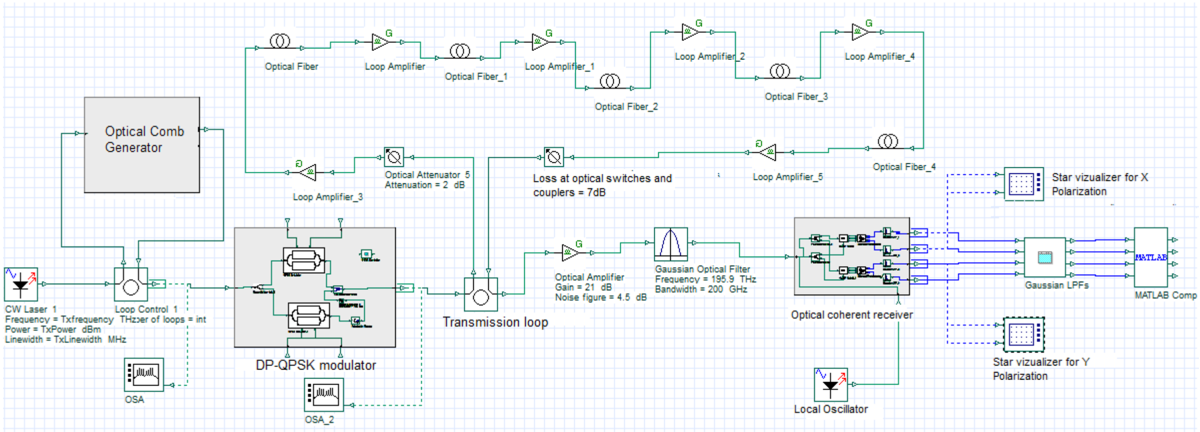


Fig. 8. System simulation pallet configured with experimental parameters [ref] for validation of the system evaluation procedure.

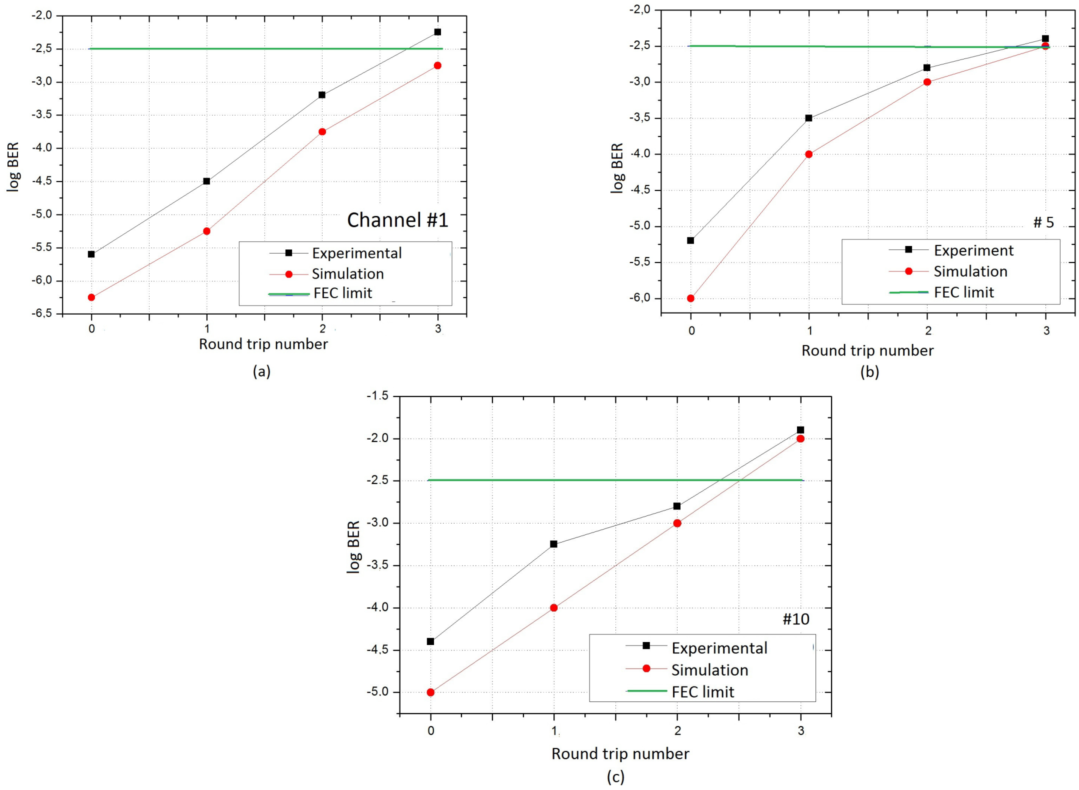


Fig. 9. BER versus round trip number in the (transmission media) recirculating loop for channel: (a) # 1, (b) #5 and (c) #10.

B. *Filter concatenation effect*

To evaluate the OCG techniques we configured a setup comprising a DP-QPSK transmitter set to 112 Gb/s, a recirculating loop with an optical fiber and a line amplifier, and a coherent receiver. After the coherent receiver we used a treatment of digital signals simulated in a Matlab environment. Figure 10 shows the system simulation pallet and Table I the main simulation parameters.

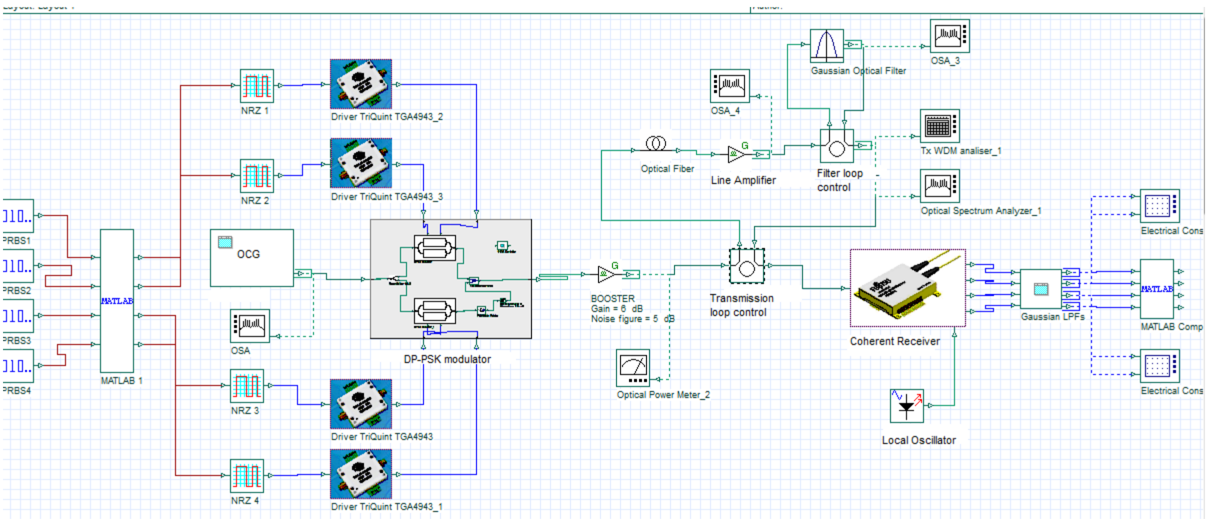


Fig.10. System setup for evaluation of the OCG techniques.

TABLE I. SYSTEM SIMULATION PARAMETERS

Parameter	Value	Unit
Bit rate	112	Gb/s
Samples per bit	4	-
Frequency shift	2	degree
Optical filter bandwidth	280	GHz
Number of optical filtering per roundtrip	1, 2, 3	
Seed laser	193.4	THz
Seed laser linewidth	0,5	MHz
Local oscillator	193.4 + frequency shift	THz
Local oscillator linewidth	0,5	MHz
Transmission fiber dispersion	16.75	ps(nm^2.km)
Transmission fiber attenuation	0.2	dB/km
Transmission fiber PMD	0.1	ps(km)$^{0.5}$
$EDFA_{Loop}$ Noise Figure	6	dB
$EDFA_{Loop}$ gain	20	dB

As we can see in Fig. 10, the system setup contains four PRBS (Pseudo-random binary sequence) generators. The four data streams are saved in the Matlab block (for further BER evaluation) and reinserted into the Optisystem pallet. The signals then go through four NRZ (non return to zero) pulse generators and electrical amplifiers, so that their amplitudes become compatible with the modulator bias voltages level. The optical comb, generated from a seed laser, is then modulated by the DP-QPSK modulator, amplified by an EDFA (booster) and inserted into the recirculation loop, which is composed by a control loop with 100 km of G.652 standard singlemode fiber (STD SMF) link and one inline EDFA, with gain set to compensate for the fiber attenuation. Within this loop, after the optical amplifier another control loop is placed for simulating the effect of cascading a given device (an optical filter, for instance). At the coherent receiver, the signal undergoes a beating with a continuous wave optical signal (generated by a local oscillator) and the resultant beam will transfer the transmitted signal characteristics from the optical to the electrical domain. The four output signals XY_{IQ} (X and Y stand for the light polarization state, I and Q standing for 'in-phase' and 'quadrature phase'), exiting the balanced photo detectors, are filtered by a 30 GHz electrical filter (when using 80 GSa/s in the DSP) or a 16 GHz electrical filter (when using 40 GSa/s). Those bandwidths are in accordance with the scope used in the experiment. Another electrical filter (22 GHz band) is used in the coherent receptor block, in Fig. 10. The pallet has been assembled according to the parameters indicated in Table I and the 10-subcarrier superchannel launched power has always been set to 1 dBm.

The first comparative analysis considered the superchannel propagating throughout a cascade of optical filters. For that, the transmission fiber control loop (Fig. 10) was set to "1" whilst the filter control loop varied. This way, the superchannel just crossed the first loop, recirculated 'n' roundtrips in the second loop and reached the coherent receiver input. The objective here was to evaluate the superchannel behavior facing a spectral narrowing, a typical situation in networks where the optical paths include a number of nodes with reconfigurable optical add and drop multiplexers (ROADMs). Note that the next generation networks, aiming to accommodate such superchannel traffic, must be able to adjust the ROADM bandwidth in a flexible and dynamic way. Particularly, for the 10-subcarrier superchannel analyzed in this paper, a minimum band of 280 GHz is necessary. Therefore, for stressing the filter concatenation issue, we considered the worst case scenario, i.e. a filter bandwidth of 280 GHz. For a global evaluation, the most representative results may be related to channels #1, #5 and #10 because in channel 10 we have observed the worst OSNR subcarrier (mainly in the RFS technique [11]) and it is, as channel #1, located at one of the superchannel edges). Channel 5 is a good candidate for suffering more effects from the interchannel interference, since it is located in the superchannel center. The resultant BER curves, as a function of the round trip number in the filter loop, are shown in Fig. 11, noting that an appropriate fitting may be used to estimate the maximum number of crossed filters when reaching the BER_{FEC} threshold.

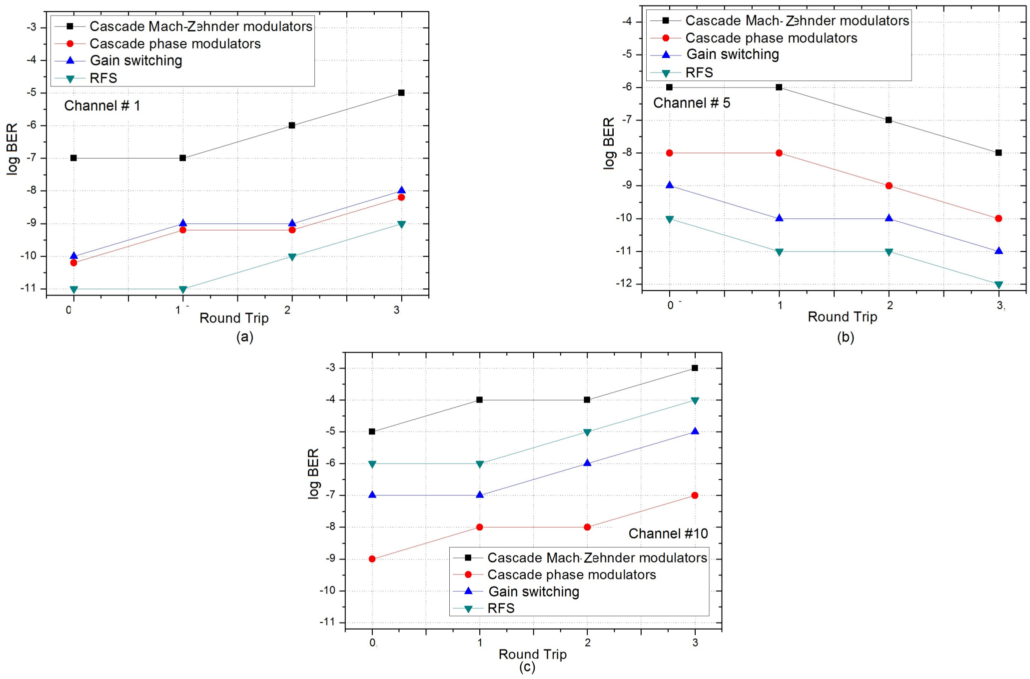


Fig. 11. BER vs. round trip number, after a cascade of optical filters, for channels: (a) #1, (b) #5 and (c) #10.

Brazilian Microwave and Optoelectronics Society-SBMO received 29 March 2013; for review 9 May 2012; accepted 1 Aug 2013
Brazilian Society of Electromagnetism-SBMag ISSN 2179-1074

C. EDFA + fiber concatenation effect

With the previous setup used as base, new simulations were carried out, but this time the loop controls were switched: the filter loop control was disabled whilst the transmission loop control varied. In this test we evaluated the simultaneous concatenation of ASE and fiber propagation effects (more likely to occur since the power launched into the 100 km fiber link has always been set to 1 dBm, a value not high enough to significantly activate the fiber nonlinear effects). That launched power precautious was necessary because the DSP module does not include, yet, a nonlinear propagation effects corrector. Figure 12 presents the BER curves, as a function of the round trip number, for channels #1, #5 and #10. The round trips were limited to 3, corresponding to propagation through 300 km of STD SMF but, from a fitting, those results may be extrapolated to estimate the maximum reach at the BER_{FEC} threshold.

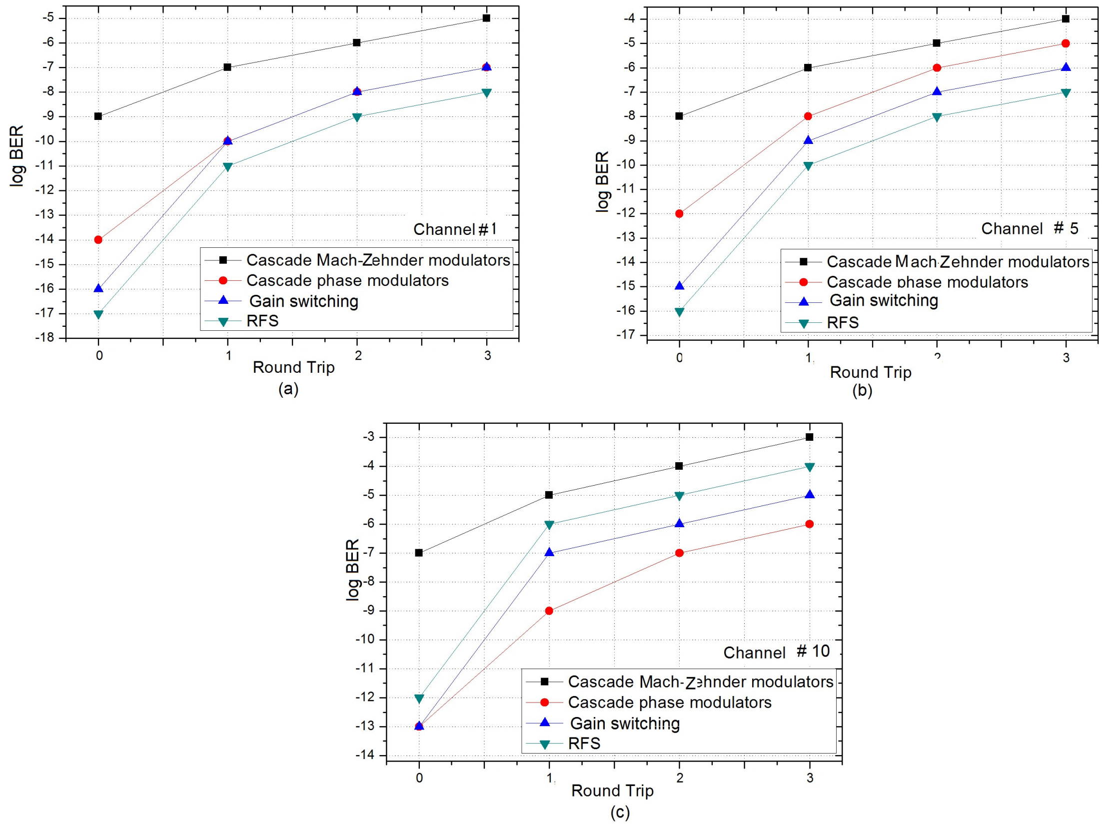


Fig. 12. BER vs. round trip number, after a cascade of optical amplifier and 100 km STD SMF, for channels: (a) #1, (b) #5 and (c) #10. The reference performance corresponds to the round trip number "zero".

VI. Discussion

A great sequence of ROADMs placed along a given optical path is a situation likely to happen in long reach optical networks. Therefore, the spectral narrowing, resultant from such filter concatenation, is an impairment that might be taken into a serious account during the network planning and design. In our simulations, we have stressed the problem by configuring the filter bandwidth without margin for any window narrowing, i.e. for a 280 GHz superchannel the filter band has been set to 280 GHz. Added to this constrain comes the fact that during the tests the signal crosses one booster amplifier and one inline amplifier, which means that it also accumulates a low level of ASE, as it happens in typical short reach links. The ASE problem may be considered not too much severe for most of the OCG techniques, but becomes worse for the lower frequencies subcarriers (#10 is the worst case) generated in the RFS technique, since it employs extra EDFA(s) on its recirculating loop. As a consequence of the filter cascade, from the results we clearly notice the BER performance degradation for the border channels (#1 and #10) in a nearly linear fitting that leads to one magnitude order increase, in BER value, per roundtrip – a similar trend seen in all OCG techniques. However, when comparing the BER performances, we also clearly notice that some techniques presented a better behavior. By taking into account that #1 has the best OSNR and #10, the worst, we may classify the techniques from worse to better. For #1, the classification is: MZ cascade, Gain switching (GS), PM cascade, RFS. For #10, the grid becomes: MZ cascade, RFS, GS, PM cascade, (here we note the impact of the ASE accumulation, intrinsic to the RFS technique, thus it falls from better performance, in the #1 evaluation, to second worse, for #10). It is really interesting to observe #5 results: the becomes better as the roundtrips progress. One should expect that they would not change, since there is no accumulation of other effects and because #5 is located in the superchannel center it should not be affected by the window narrowing. However, the improvement on the BER values make us wonder what was also improving as the loop recirculation progressed. One possible explanation is that some level of interchannel interference (ICI) occurs (due, for example, to a non-perfect mutual orthogonality between subcarriers). In that case, as #1 and #5 are progressively being cut, the ICI is progressively being reduced. More simulations will be carried out to investigate this hypothesis and the results will be published after that. For #5, the grid from worse to better OCG technique becomes: MZ cascade, PM cascade, GS and RFS. Considering the FEC limit of 3.8×10^{-3} we may estimate how many cascaded filters each technique may tolerate. The results are summarized in Table II.

TABLE II OCG TECHNIQUES FACING SPECTRAL NARROWING (FROM WORSE TO BETTER)

#1 (Filters below FEC limit)	**#5 (Filters below FEC limit)**	**#10 (Filters below FEC limit)**
MZ Cascade (~7)	MZ Cascade (too high to be estimated)	MZ Cascade (~4)
Gain Switching (~8)	PM Cascade (too high to be estimated)	RFS (~5)
PM Cascade (~9)	Gain Switching (too high to be estimated)	Gain Switching (~8)
RFS (~9)	RFS (too high to be estimated)	PM Cascade (~8)

In the second analysis, we have presented the results for up to 300 km (3 roundtrips) within the loop. For #1, the MZ cascade led to a BER of 10^{-5}, the GS and PM cascade resulted in 10^{-7}, whereas the RFS technique provided a BER of approximately 10^{-8}. For # 5, the MZ and PM cascade led to a BER of approximately 10^{-4} and 10^{-5}, respectively, the GS resulted in a BER of 10^{-6} and the RFS in a BER of 10^{-7}. For # 10, the performance for the RFS was worse due to the fact that this subcarrier has a worse OSNR. As explained before, that is due to the comb generation process where the last channel ends up accumulating more noise from the optical amplifiers than the other channels.

  ISSN 2179-1074

As in the previous study, the BER degradation trend is similar to all OCG techniques and, by taking into account the FEC limit, we may also extrapolate the results to estimate the maximum reach that may be obtained by each technique. The results are summarized in Table III.

TABLE III OCG TECHNIQUES FACING ASE ACCUMULATION AND LINEAR PROPAGATION EFFECTS

#1 (Max. reach below FEC limit)	#5 (Max. reach below FEC limit)	#10 (Max. reach below FEC limit)
MZ Cascade (~600 km)	MZ Cascade (~500 km)	MZ Cascade (~400 km)
PM Cascade (~800 km)	PM Cascade (~600 km)	RFS (~500 km)
Gain Switching (~800 km)	Gain Switching (~700 km)	Gain Switching (~600 km)
RFS (~900 km)	RFS (~800 km)	PM Cascade (~700 km)

VII. CONCLUSION

Three techniques of optical comb generation, aiming the assemble of a superchannel transmitter, have been described: cascade of modulators, recirculating frequency shifting (RFS) and laser gain switching. They were configured in a setup designed for simulating the following impairments: (i) spectral narrowing due to optical filter concatenation; (ii) ASE accumulation combined with linear propagation effects. Four Optical Comb Generators (OCGs) have been tested, all of them generated 10 subcarriers and the results presented here were related to subcarriers #1, #5 and #10.

Overall, the MZ cascade technique has provided the worst performance but the PM cascade has proved to be a much better option. The RFS technique presented a good performance except for #10, which must been taken into account in a fairness criterion of guaranteeing a good performance for all subcarriers. Due to its simplicity and lower cost, the Gain Switching appears as a good candidate for superchannel transmitter modules, however, more test are required before one will be able to point out the best technique. Some of them might include the combination of the RFS with the PM cascade, in order to obtain a large number of lines and a better performance, at a price of more complexity and cost.

The OSNR degradation due to ASE accumulation appears to be one of the most critical aspects of a superchannel system design. Some OCG techniques require extra amplification due to the insertion loss of its devices. The Gain Switching has the advantage of not using so many components that will require extra amplification; therefore its OSNR may be high enough to guarantee long reach propagation without significant ASE addition. This is a promising technique and will be object of further studies.

The subject investigated in this paper presents many challenges. The RFS technique has an advantage over the others because it can generate multiple channels, as the others are limited to around 10 channels, unless they are combined with more modulators in cascade. The combination of RFS and PM cascade appears to be an attractive solution and should be, also, further investigated. Among others, issues that also require further analysis are: superchannel stability and signal processing for dealing with interchannel interference (ICI) and nonlinear propagation effects.

ACKNOWLEDGMENT

The authors are grateful to Julio C. F. de Oliveira, head of the Optical Communication Group at CPqD Foundation and, in particular, to the researchers Daniel M. Pataca, for the helpful discussions and experimental data support, and Vitor Bedotti, for the offline processing support.

REFERENCES

[1] P. J. Winzer, "Beyond 100G Ethernet". *IEEE Communications Magazine*, v.48, n.7, jul. 2010.

[2] S. Chandrasekhar, Xiang Liu, "OFDM based Superchannel transmission technology", *Journal of Lighwave Technology*, v. 30, n. 24, pp. 3816-3823, 2012.

[3] F. D. Simões, D.M. Pataca, M. L. Rocha, "Design of a comb generator for high capacity coherent-WDM systems", *IEEE Latin America Transactions*, v. 10, n. 3. pp. 1690-1696, 2012.

[4] http://www.optiwave.com/products/system_overview.html, accessed in 20/03/2013.

[5] J. Yu, et al. "Generation of coherent and frequency-locked multi-carriers using cascaded phase modulators for 10 Tb/s optical transmission system", *Journal of Lightwave Technology*, v. 30, n. 4, pp. 458-465, 2012..

[6] T. Kawanishi et al., "Optical frequency comb generator using optical fiber loops with single-sideband modulation", IEICE Electronics Express, v. 1, n. 8, pp. 217-221, 2004.

[7] P. M. Anandarajah et al., "Generation of coherent multicarrier signals by gain switching of discrete mode lasers", *IEEE Photonics Journal*, v.3, n.1., pp. 112-122, 2011.

[8] D. M. Pataca, H.H. Carvalho, C.B.F. Adami, F.D. Simões, J.C.R.F. Oliveira, "Transmissão de um supercanal OFDM de 1,12 Tb/s por 452 km com eficiência espectral de 4 b/s/HZ", *Proceedings of SBrT 2012*.

[9] D. M. Pataca, P. Gunning, M.L. Rocha, J.K. Lucek, R. Kashyap, K. Smith, D.G. Moodie, R.P. Davey, R.F. Souza, and A.S. Siddiqui, "Gain-Switched DFB Lasers", *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vV. 1., n. 1, pp. 44-63, 1997-1998.

[10] Vitor Bedotti Ribeiro, "Filtros digitais para recepção coerente em 112 Gb/s de sinais ópticos com modulação QPSK e multiplexação por divisão em polarização", Dissertação de Mestrado, FEEC-UNICAMP, 31/08/2012

[11] D. M. Pataca, F. D. Simões, M. L. Rocha, "Optical frequency comb generator for coherent WDM system in Tb/s applications", IEEE/SBMO IMOC 2011.

  ISSN 2179-1074