Optical Comb Generation Techniques

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***Abstract*—We present a study of three techniques for generation of optical combs which can be used, in association with other modulation formats, in transmitters and receivers of high-capacity systems. Those comb generators produce a set of mutually orthogonal optical signals thus reducing the need for guard bands between channels and also making more efficient use of the available optical bandwidth. The following techniques are described in terms of their main features and system performance: i. cascade of Mach-Zehnder modulators; ii. recirculating frequency shifting; iii. discrete mode laser.**

***Index Terms*— high capacity optical transmission; optical comb generator; superchannel.**

I. Introduction

The main challenge for the research on systems running at rates exceeding 100 Gb/s is to demonstrate, by means of different modulation and reception techniques, the optical transmission at rates tending to, at least, 400 Gb/s and 1 Tb/s over long distances (hundreds of kilometers). As the system capacity increases, the challenges become more severe and the alternatives for addressing them become more complex. Unfortunately, it is usual that the proposed solutions add new problems as side effects that will also need to be addressed. In general, those challenges are related to methods of generating and receiving new modulation formats, to broadband and low noise optical amplification techniques and to the combat of noise and distortion, generated in the transmitter and receiver, in combination with linear and nonlinear propagation effects [1-3].

In this context, optical OFDM (orthogonal frequency division multiplexing) has become a promising technique for high spectral efficiency and dispersion resilient transmission, where the generation of optical multi-carrier sources represents a paramount issue. In multi-carrier transmission, besides the orthogonality between carriers aspect, it is necessary to have them frequency-locked, in order to take advantage of OFDM for high spectral efficiency. One of the techniques that enable transmission of several Tb/s per fiber relies upon the use of coherent and orthogonal multi-carriers originated from a single laser source, thus resulting in a high aggregate capacity that exploits parallel processing techniques, with moderate speeds per carrier and high spectral efficiency. Such high bit rate signal, produced from a single laser, comprising multiple carriers locked in frequency and modulated in a synchronous mode, is known as *superchannel*. In this signal, the interference between the orthogonal modulated carriers can be eliminated by controlling the phase of adjacent channels.

It has been shown that a channel, among several others, can be detected, with minimum penalty caused by interference between channels, when the following conditions are met [4]:

(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 carriers the smaller should be the difference between the frequency separation (between carries) and the symbol transmission rate of each one. That means, it is crucial to generate stable carriers, without variation of the frequency interval between them and with same transmission rate for each one.

A typical transmitter is illustrated in Fig. 1, where the superchannel is generated from a laser seed incident on an optical comb generator (OCG) block.

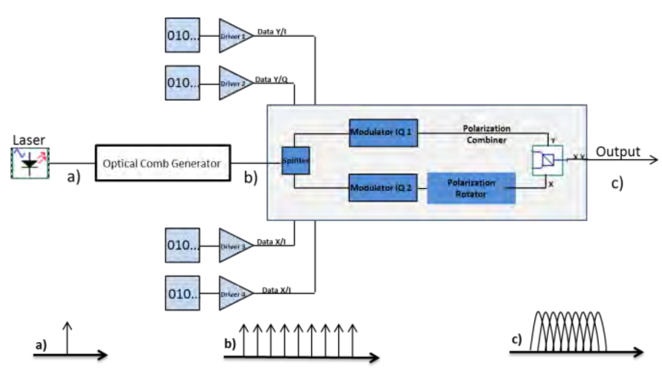

Fig. 1. OFDM transmitter with frequency locked subcarriers.

As indicated in Fig. 1, after the comb generation, the next step is the modulation of each optical channel in a DP-QPSK (dual polarization quadrature phase-shift keying) modulation scheme. At this stage, to establish the mutual orthogonality among subcarriers, they should be spaced by a value equal to the symbol rate. Once the orthogonality is achieved, the need for a guard band between adjacent subcarriers becomes dispensable. At the exit of the modulator, the superchannel is ready to be transmitted.

In this paper, we present a theoretical study of three techniques for generation of optical combs which can be used, in association with other modulation formats, in transmitters and receivers of high-capacity systems. Those comb generators produce a set of mutually orthogonal optical signals thus reducing the need for guard bands between channels and also making more efficient use of the available optical bandwidth. By using a commercial optical system simulator (Optsystem v. 9.0), the following techniques will be described in terms of their main features and system performance:

(i) Cascade of Mach-Zehnder modulators (MZM) - commonly used to generate signals with two to eleven carriers; its limitation is the small number of generated carriers, which is determined by the MZMs electro-optic bandwidth and by the maximum amplitude of the driver signal;

(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 [5]; and

(iii) Discrete mode laser (DM) driven by a sine wave – similar to gain switching in semiconductor lasers resulting in phase locking at the output. Its main advantages are simplicity and low cost [6].

The paper is organized as follows. Sections II, III and IV describe the main principles of each technique, section V compares their behavior in terms of system performance and section VI presents some conclusions.

II. CASCADE OF MODULATORS

In this technique, two cascaded Mach-Zenher modulators (MZ) are driven by sinosoidal electrical waves. It is important to notice that, in this technique, not just MZ modulators may be cascaded, the set up may comprise a cascade of phase modulators (PM), or a combination between 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 to be observed is that the amplitude of all subcarriers must be equalized by a special scheme. In Fig. 2, the optical comb with 10 lines, generated by two MZs, are separated by a WDM demux that allows the use of variable attenuators for adjusting the amplitude of each channel. Once the comb lines are flat, they are modulated and, then, combined in a WDM mux before being launched into the transmission fiber.

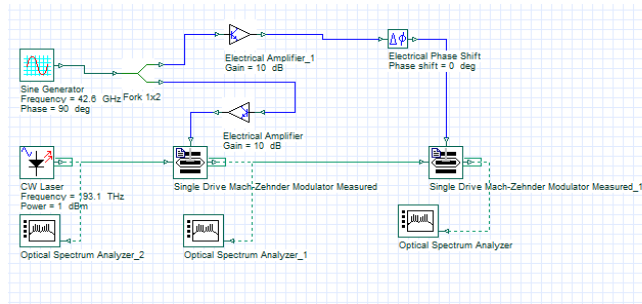

Fig. 2. Simulation pallet for the modulator cascade technique.

Figure 3 shows the optical spectrum of 10 comb lines, resultant from this technique, before the modulation has been applied to the comb.

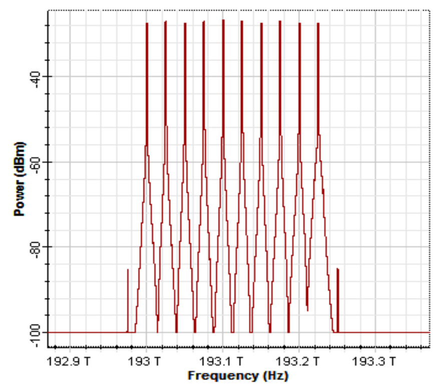

Fig. 3. Optical comb comprising 10 subcarriers, spaced by 25 GHz, generated by the cascade of modulators technique.

III. RECIRCULATING FREQUENCY SHIFTING, RFS

In the RFS technique, the optical signal, generated by a laser source, is shifted, in frequency, within a recirculation loop. This Comb-Generator (CG) consists of a singlemode laser, a 2x2 optical coupler, a double Mach-Zehnder (MZ) optical modulator, an optical amplifier (Erbium-doped fiber amplifier, EDFA), to compensate for the loop losses, and an optical filter, for limiting the number of generated carriers and the level of amplified spontaneous emission noise within the loop, as illustrated in Fig. 4. According to the figure, an optical signal (coming from a laser source), is continuously injected into the loop through one of the coupler input ports, and circulates on the loop. After each round trip part of the signal outputs the loop and part returns to it.

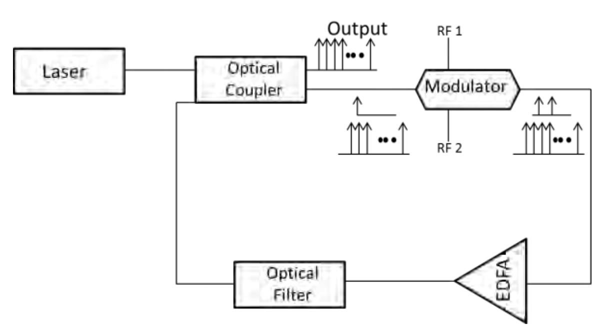

Fig. 3. Comb generator based on the recirculating frequency shifting technique.

In the loop, the optical modulator is optically controlled by a polarization controller and electrically driven by two RF sine waves. Its biasing points are adjusted in such a way to generate a single side-band suppressed carrier signal (SSB-SC), which is than amplified and filtered. The action of the filter is crucial as it limits the optical noise and cuts off the optical carriers that exceed its bandwidth. Note that the filter output is added to the signal coming from the laser and inputs the loop again.

At each round trip, the optical modulator shifts the signal spectrum in a frequency equal to the RF frequency applied to it. After many round trips, the circulating signal spectrum is shifted to outside of the filter bandwidth, thus limiting the number of comb lines at the generator output.

The simulation pallet is shown in Fig. 4, and Fig. 5 presents the optical spectrum at the comb generator output.

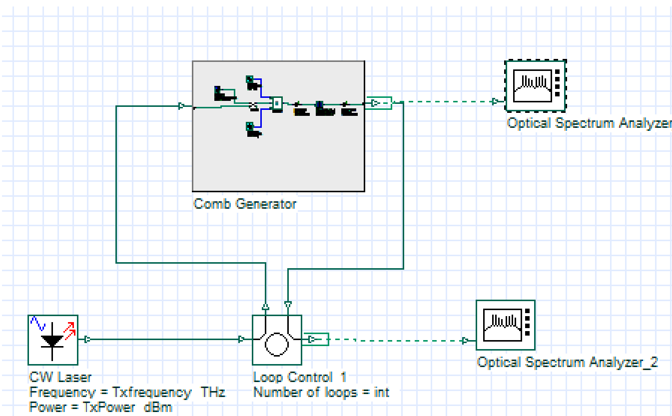

Fig. 4. Simulator pallet for the recirculating frequency shifting technique.

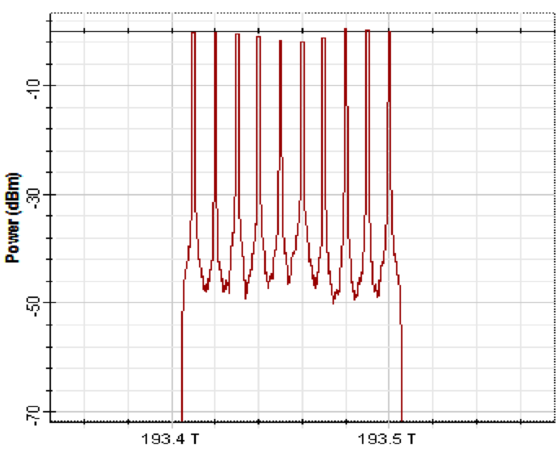

Fig. 5. Optical spectrum of 10 comb lines, spaced by 25 GHz, for the RFS technique.

IV. Discrete Mode Laser, DM

In this section, we describe the comb generation technique that uses a laser directly modulated by an intense sine wave, which works similarly to the gain switching, resulting in a comb with phase synchronism among lines. This technique has as on the main advantages the simplicity and low cost. [7] In our implementation, a sinusoidal electrical signal of 25 GHz was amplified and directly applied to a laser aim (in the simulator) for direct modulation. The process of generating pulses is similar to the method of gain switching, as illustrated in Fig. 6, where the laser continuous wave, tuned at 1552.52 nm, is gain switched by a sinusoidal 25 GHz signal. This shows that this technique can be employed as a transmitter cost efficient in transmission systems requiring uniform spacing between the optical subcarriers.

Once the comb has been generated, its amplitude is equalized by a set of variable attenuators placed in between a demux and a mux. The optical comb spectrum at the laser output is seen in Fig. 7.

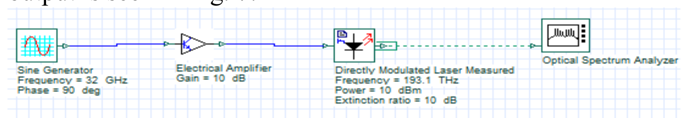

Fig. 6. Simulator pallet for the discrete mode laser technique.

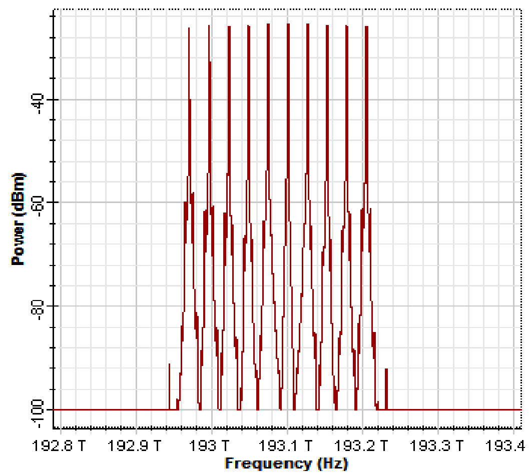

Fig. 7. Optical spectrum of 10 comb lines, spaced by 25 GHz, for the discrete mode laser technique.

V. Performance Comparison

To evaluate the three techniques described in the previous sections, we configured a simulation arrangement comprising a DP-QPSK (dual polarization quadrature phase shift keying) transmitter set to 112 Gb/s, a recirculating loop comprising an optical fiber and a line amplifier and a coherent receiver. After the coherent receiver we used a treatment of digital signals simulated by Matlab [8]. Figure 8 shows the simulated system pallet used on the simulator.

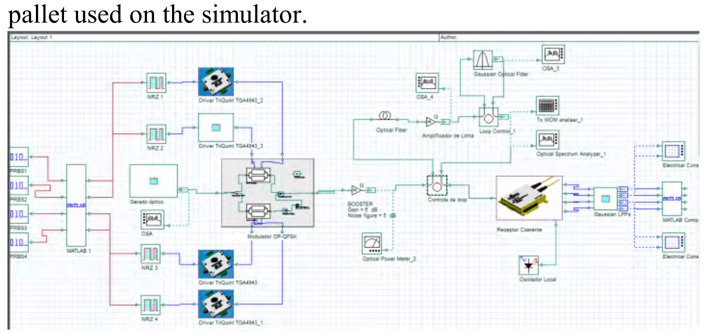

Fig. 8. System set up.

As we can see in Fig. 8 the system contains four PRBS (Pseudo-random binary sequence).generators. These data will be saved in the Matlab environment and inserted into the Optisystem pallet. Upon passing the Matlab modules, they go through a pulse generator NRZ (non return to zero), before being inserted into the DP-QPSK modulator. These signals are encoded in NRZ electrical amplified so that their amplitudes are consistent with the bias voltages of the modulator. The optical comb generated by the seed laser is then modulated by the DP-QPSK modulator and then inserted into the recirculation ring which is composed by a control loop, an optical fiber (100 km) G.652 SMF, and an amplifier with a gain to compensate for the fiber attenuation. After the optical amplifier another control loops is placed for further studies (e.g. for evaluating the effect of a cascade of filters). At the coherent receiver, the signal undergoes a beating with the local oscillator, ant the resultant will transfer the signal characteristics from the optical domain into the electrical domain. The four output signals from the balanced photodetectors XYIQ (X and Y polarization, in-phase and quadrature) are filtered with electrically band of 30 GHz. After the filtering those signals are processed in Matlab to perform digital signal processing.

With the system assembled according to Table 1 and a launched power into the fiber of 1 dBm, for all three types of comb generation techniques studied, the resultant BER (bit error rate) curves are shown in Figs. 9, 10 and 11, for channels 1, 5 and 10, respectively.

TABLE I
SYSTEM SIMULATION PARAMETERS

Parameter	Value SIZE	Unit
Bit rate	*112*	*Gb/s*
Samples per bit	*4*	
Round trip number	*1*	
Frequency shif	*2*	*graus*
Optical filter bandwidth	*280*	*GHz*
Seed laser frequency	*193,4*	*THz*
Seed laser linewidh	*0,5*	*MHz*
Local oscilator frequency	*193,4 + desvio de frequência*	*THz*
Local oscillator linewidh	*0,5*	*MHz*
Fiber dispersion	*16,75*	*ps(nm^2.Km)*
Fiber attenuation	*0,2*	*dB/Km*

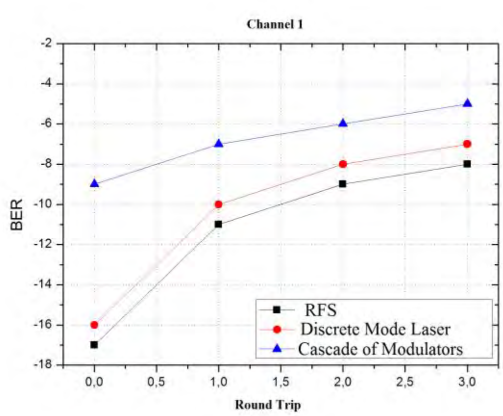

Fig. 9. BER versus round trip (100 km long, each), for Channel 1.

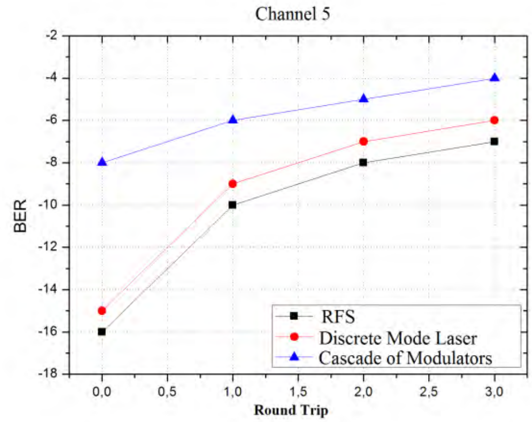

Fig. 10. BER versus round trip (100 km long, each), for Channel 5.

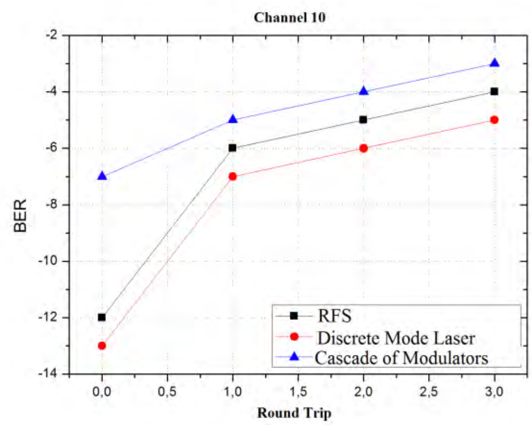

Fig. 11. BER versus round trip (100 km long, each), for Channel 10.

VI. CONCLUSION

Three techniques for an optical comb aiming the generation of optical superchannels (OFDM transmission) have been presented: cascade of modulators, RFS and discrete mode lasers and configured in a pallet set up for a system performance evaluation. Considering the FEC limit, for three rounds on the loop (total of 300 km), the RFS technique provided BER, for channel 1, of approximately 10^{-8}, whereas the technique of cascaded modulators led to a BER of 10^{-5}, and the discrete mode to 10^{-7}. For channel 5, the discrete laser mode resulted in a BER of 10^{-6}, the cascaded modulators resulted in a BER of approximately 10^{-4}, and the RFS in a BER of 10^{-7}. For channel 10, the performance for the RFS was worse due to the fact that channel 10 has a worse signal to noise ratio. That is because of the comb generation process where the last channel ends up accumulating more noise from the optical amplifiers than the other channels.

The cascade modulators technique has provided the worst performance in all simulations, and that may be due to the insertion loss of the modulators, which ends up worsening the signal to noise ratio for all channels. For that reason, the channels end up needing a greater amplification before being launched into the fiber - that does not occur in the discrete mode laser technique because it needs only one RF amplifier before the signal is inserted into the laser. Furthermore, in the RFS technique, the optical amplifiers gain within the loop help in maintaining a good signal to noise relationship even with the additional amplified spontaneous noise. Furthermore, this technique has an advantage over the others, because it can generate multiple channels, as the other two are limited to around 10 channels, unless they are combined with more modulators in cascade.

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