Development of a 10 Gbit/s Optical Soliton Source

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1. ABSTRACT

In this work we demonstrated the feasibility of a 10 Gbit/s optical soliton source based on direct modulation of a semiconductor laser. We also show that it is possible to reduce substantially the frequency chirp, induced by the direct modulation process, with a narrow optical filter. A peak power greater than 100 mW is achieved with an optical signal-to-noise ratio (OSNR) better than 39 dB. We measured the output timing jitter of the source and we show that its main contribution is due to the laser noise. We successfully test our source in a 45 km 5 channels WDM system. The stability and easy assembly of this type of sources make them attractive for upgrading single or multi-channel chromatic dispersion limited optical communication systems.

Keywords: Optical source, solitons, frequency chirp, optical signal-to-noise ratio, timing jitter

2. INTRODUCTION

As today's optical communication systems evolves to multiple wavelengths and even higher bit rates and distances, chromatic dispersion and nonlinear effects in the fibers present serious limitations. There is a conjugated effect between chromatic dispersion and self-phase modulation that shapes the optical pulses during propagation. Soliton pulses to propagate without shape distortion use this interplay, which make them very attractive to implement high-speed optical communication system in a dispersive and nonlinear medium as an optical fiber. However, to implement optical solitons communication systems, stable short pulses sources are required. In a 10 Gbit/s system the solitons temporal width should be as short as 20 ps, which it is 1/5 of the bit period, in order to prevent strong signal degradation due to nonlinear interactions between adjacent pulses [1]. The optical field envelope at the source output should be close to secant hyperbolic in order to allow easy solitons formation and reduce the dispersive waves. The pulses central frequency chirp must be

controlled because a large amount of chirp will induce a strong pulse transmission broadening due to chromatic dispersion. The output peak power must be enough to excite the nonlinear effects in the fiber and to generate the soliton pulses. Simultaneously, it is required a high OSNR in order to achieve a low bit-error rate (BER) at the system end. The amount of energy in the logical zeros time slots should be as low as possible in order to allow an easy decision, between the logical zeros and ones at the receiver. Besides all this requirements, the soliton source must be able to generate 10 billions of pulses per second with very low timing jitter and keep operating smoothly during large periods of time.

3. SHORT PULSE GENERATION

Several techniques have been presented in the specialized literature for short pulse generation. Fiber laser techniques are usually able to produce very short pulses with low central frequency chirp. However, fiber laser sources use in telecommunications systems are limited by difficulties in obtaining high pulses repetition rates and source stable operation outside the laboratory, during long periods of time. Up to now, semiconductor laser based techniques have been proved to be more suitable for telecommunications systems. Among the semiconductor laser based techniques, several complex devices with very high electrical bandwidth have been presented in which the laser and the modulator are all integrated in the same package. More simple and affordable techniques are based in direct or external modulation of a semiconductor laser light. Several different schemes of external modulation have been shown in which a Mach-Zehnder interferometer modulator placed in front of the laser is able to generate short pulses at high repetition rates. A major drawback of this technique is the need of complex high-speed electronic circuits to shape the signal prior to feed the Mach-Zehnder arms. A more simple and attractive technique for telecommunications purposes is based on direct modulation of the semiconductor laser, see figure 1.
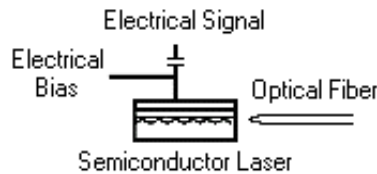
Figure 1 – Short pulse generation by means
of direct modulation a semiconductor laser.

This gain-switching technique is based on the use of the first relaxation oscillation of the laser transitory response to generate very short pulses. As it is well known, when a semiconductor laser is turned on and off the output light intensity present several relaxation oscillations, which are the result of the interplay between the carriers and the photons in the semiconductor junction, as can be seen in figure 2a. Although, the amplitude of these relaxation oscillations decreases exponentially with time, they present a major performance limitation factor in high-speed NRZ optical communication

systems. However, the first relaxation oscillation can be used to generate short pulses if the laser injection current is turned off before the second oscillation appears, preventing its formation, see figure 2b [2].

a)   b)
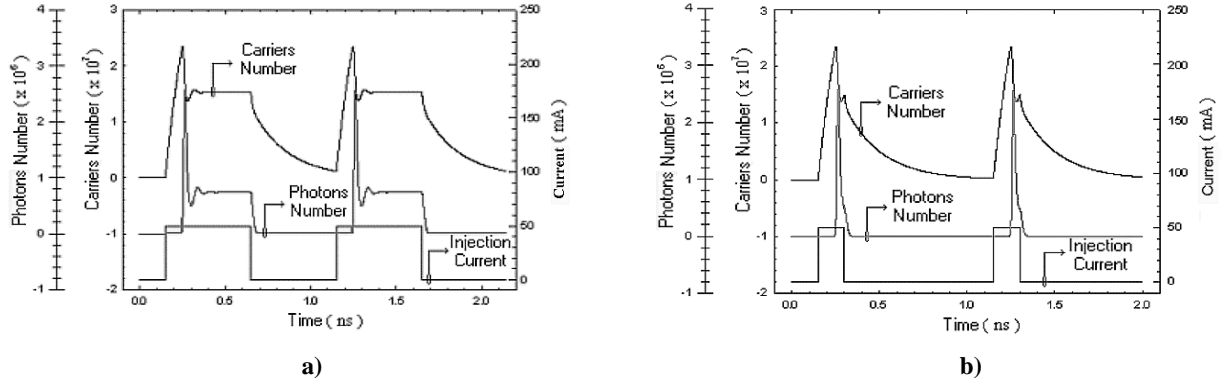
Figure 2 - Time variation of the photons and carriers number as result of the inject current variation

At first, this can seem to lead to the need of complex high-speed electronic circuits to turn the current off before the second oscillation, although, as we show, this is easily achievable by adjusting the laser bias current to a proper level. Using this technique we are able to generate pulses as short as 17 ps, as can be seen in figure 3a.

a)   b)
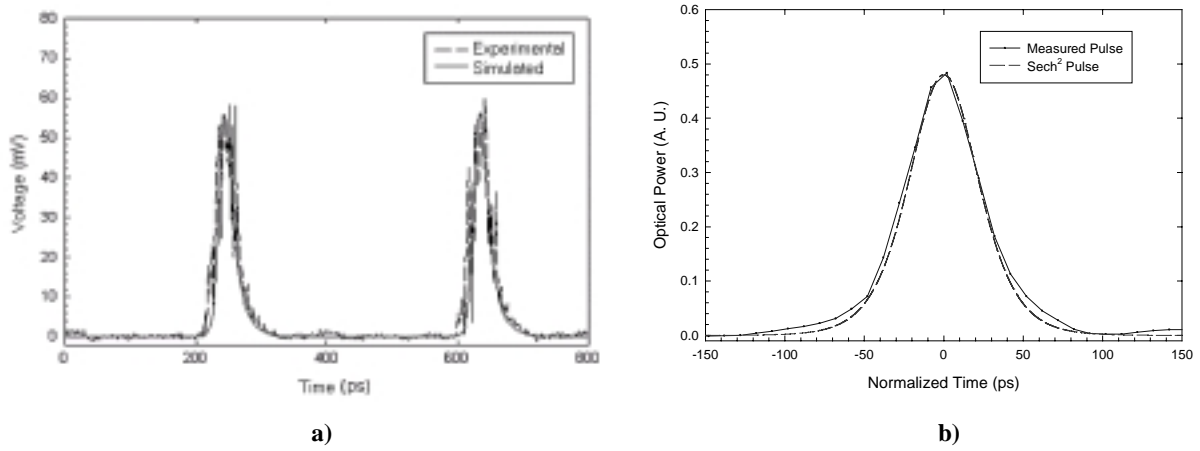
Figure 3 – **a)** Experimental and simulated pulses. **b)** Measured pulse and secant hyperbolic square shape.

In figure 3b, we compare the theoretical soliton intensity shape with the pulse shape obtained in the laboratory measurement and the shapes are very similar.

4.   OPTICAL FREQUENCY CHIRP

The technique proposal in this work to obtain short pulses is based on gain-switching. Gain-switching consists in changing the semiconductor optical cavity gain rapidly from a low to a high value. The laser is bias in a way that the modulation

current changes the injection current from a value well below threshold to a value well above threshold. When the injection current is bellow threshold the carriers and photons density is small, when the current is switched to a value above threshold the carriers density increases rapidly, while the photons density remains small until the stimulated emission process becomes dominant, see figure 2a. At that point, the optical gain in the cavity is very high making the photons density to increase rapidly; this saturates the cavity gain and originates the first relaxation frequency peak. If the duration of the injection current pulse is chosen such that the current is turned off before the second relaxation frequency peak, a short optical pulse is obtained, as it is shown in figure 2b.

A shortcoming of the gain switching method is that optical pulses are considerably chirped. The chirp is intrinsic to the process of direct modulation of a semiconductor laser and is due to the change in the refractive index of the laser cavity induced by the carriers density change. The optical frequency chirp produces a considerable broadening in the pulse spectrum that, if not properly controlled, it is translated into a time broadening after fiber propagation due to the chromatic dispersion. For a 17 ps soliton width we should expect a spectrum width of about 10.5 GHz, around the laser central frequency. However, as we can see in figure 4, we measured in the laboratory a spectrum width of about 34 GHz. Besides that for a chirp free soliton we should expect a symmetric secant hyperbolic square spectrum shape. The spectrum presented in figure 4 is far way from a symmetric spectrum and we clearly see the broadening in the left side due to the frequency chirp.
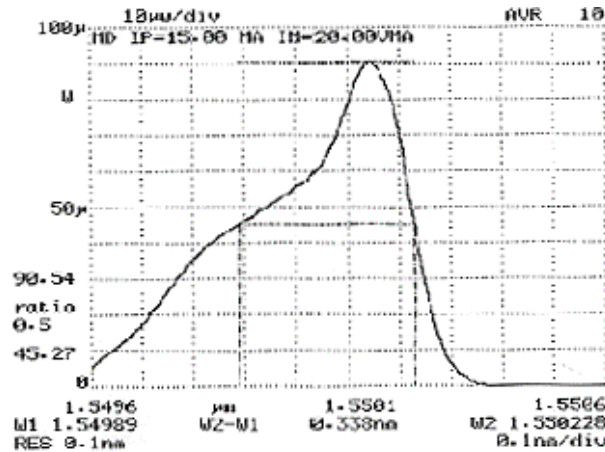

Figure 4 - Optical spectrum for a 17 ps pulse obtained by gain-switching

In order to reduce the pulse spectral width the pulse was optically filtered width a narrow filter. A Fabry-Perot filter with a bandwidth of 0.16 nm was used, and as can be seen in figure 5a, the filter reduces considerably the pulse spectrum and shapes the spectrum in a more likely secant hyperbolic square shape, as it is desirable. The optical filter also produces an effect in the pulse time domain. However, this effect is small, as can be seen in figure 5b. After the optical filter we measured a soliton width of about 23 ps, which is still suitable for a 10 Gbit/s soliton system.
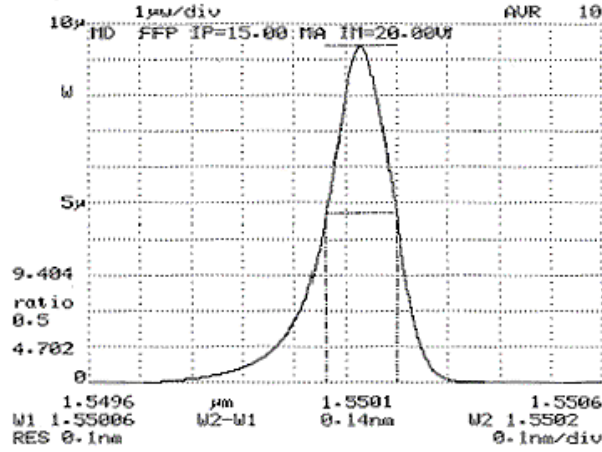
a)
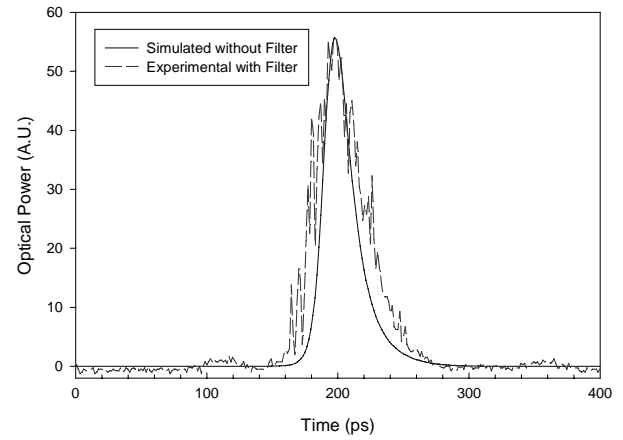
b)

Figure 5 – **a)** Optical spectrum for the optically filtered pulse. **b)** Temporal
pulse with and without optical filter.

In figure 6 are shown the time bandwidth product in function of the modulation and polarization current for the soliton source with the Fabry – Perot filter. For a polarization and modulation currents of 15.00 mA and 20.00 mA, respectively, the value for the time bandwidth product is 0.6, which is still quite above the 0.315 value for a free chirped soliton but it is already acceptable for a 10 bit/s soliton system.
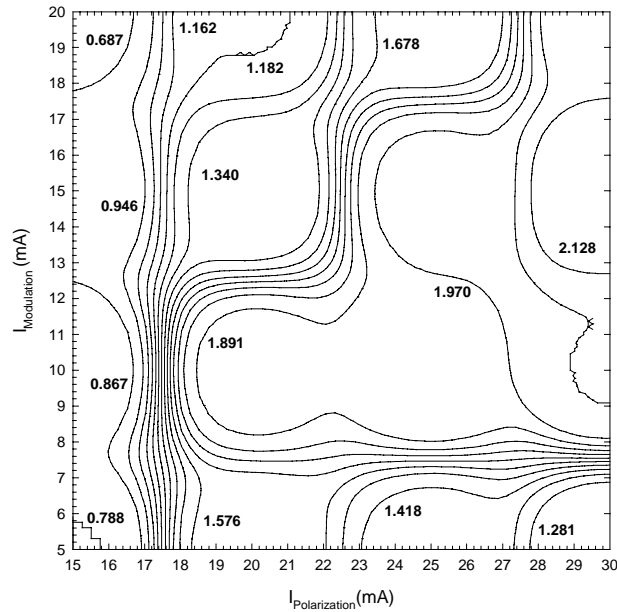
Figure 6 – Time bandwidth product as function of the modulation and polarization currents
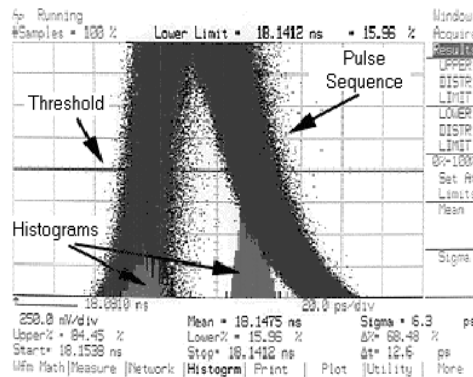
5. TIMING JITTER

In figure 7, we show an eye diagram obtained with the output signal of the soliton source. From the eye diagram it is clear that the output pulses sequence have a considerable amount of timing jitter. Which it is the same of saying that are a considerable amount of timing uncertainty in the pulses generation process. As the tolerance of communication systems to the varying arrival time of the pulses is limited, we must be careful with all the processes that introduce temporal jitter in the system.
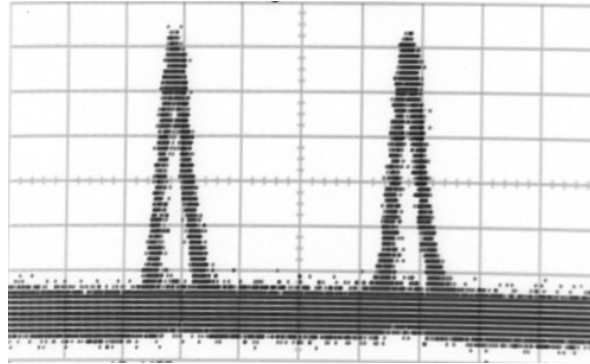
Figure 7 – Eye diagram at the output of the soliton source.

The jitter was measured at the soliton source laser output, using an oscilloscope able to trace an histogram based on the cross time of a user imposed threshold, as can be seen in figure 8. As the shapes of the obtained histograms are approximately gaussian, the timing jitter can be assumed to have a gaussian distribution with approximately a 6 ps standard deviation.


Figure 8 – Timing jitter measured

Three sets of 10 standard deviation measurements were made, as can be seen in figure 9. Two sets of measurements were obtained with two different high-speed receivers available in the laboratory. A major difference between the receivers is that one, the HP11982A, have an electrical amplification circuit, and the other, the HP83440C, does not. As can be seen in figure 9, the results obtained with the two receivers are just slightly different and from the data sheets parameters of the HP83440C fotodetector we are able to estimate a noise electrical spectral density introduced by the receiver better than 324

pA^2/Hz, which according numerical simulations results introduce less than 1 ps in the output pulse timing jitter standard deviation. Which clearly are not able to explain completely the 6 ps measured in the laboratory. The third set of measurements, present in figure 9, is obtained directly from the electrical clock signal. If we take into account the limited precision of the oscilloscope trigger circuit generator, which according to the manufacture is of the order of 2 ps, we conclude that the electrical clock signal timing jitter is negligible.
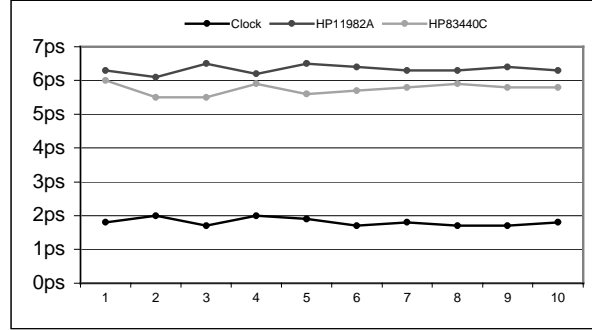
**Figure 9** – Three sets of 10 timing jitter measurements

We were also able to confirm that from the electrical clock spectral line width, which is small than 10 Hz, see figure 10. Assuming a lorentzian spectral width we estimated a timing uncertainty in the clock period of the order of few fentoseconds, well bellow the timing jitter present in figure 8.
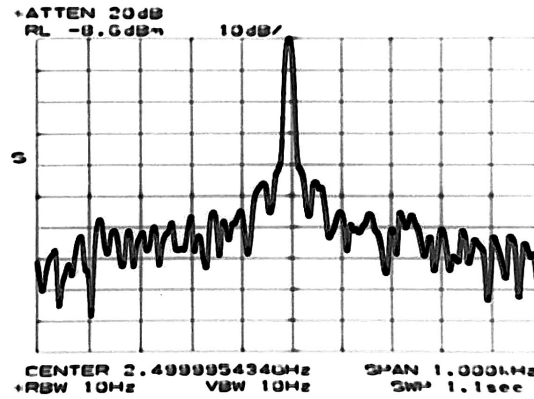
Figure 10 – Spectral line width of the clock signal

So, the major contribution to the timing uncertainty in the pulses generation process should arise from the laser noise. The semiconductor laser used in the soliton source was previously characterized [3, 4]. Taking into account the laser noise in the numerical simulation and disregard all the other effects a 4.5 ps standard deviation for the output timing jitter was obtained. Showing the main contribution of the laser noise in terms of timing jitter measured at the laser output. Physically this can be understood taking into consideration that when the drive current is in the low level the photon population in the laser active region is very small and the spontaneous emission process is dominant. Although the photon population is small, it does

have a major impact in the timing jitter because it determines the laser initial conditions for the pulse generation process. As we can see in figure 11, there is a delay between the current increase and the increase in the photon population. The number of photons in the laser active cavity, during the transition from the low to high level of the injection current, determines this delay. This number is governed by the spontaneous emission process and consequently is a random number, given origin to a random turn-on time [5].
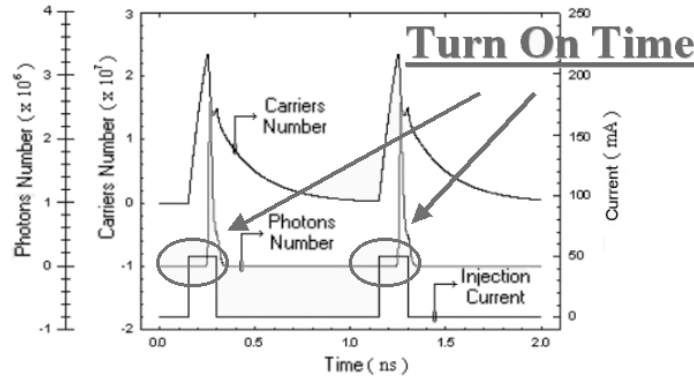

Figure 11 – Turn-on time in the pulse generation process

If we take into account the effect of the laser noise and the limited precision of the oscilloscope trigger circuit we obtain from expression 2, a standard jitter deviation of 5 ps, which agrees with the value obtained in the laboratory measurements. In expression 2, was taken into account that there is no correlation between the oscilloscope uncertainty and the laser noise.

$$\sigma_{\text{Timing Jitter}} = \sqrt{\sigma^2_{\text{Measured Value}} - \sigma^2_{\text{Oscilloscope Uncertainty}}} \qquad (2)$$

In order to simulate the timing uncertainty of the soliton source, a laser model that takes into account the laser noise was considered and an artificially uncertainty in the electrical clock signal period of 1.8 ps was introduced, to take into account the limited precision of the oscilloscope trigger circuit. As we can see in figure 12, the simulation results present a good agreement with the measurements.
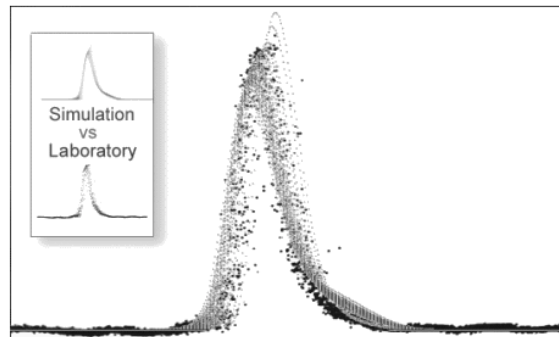

**Figure 12** – Comparison between measured and simulated eye diagram

6. SOURCE TEST

The complete arrangement of the soliton source is presented in figure 13. A Mach-Zehnder interferometer is used to block the pulses in the logical zeros time slot, in order to modulate the pulses sequence. As can be seen in figure 12, the arms of the Mach-Zehnder are feed with the data signals. In figure 14 we can see a modulated pulse sequence at the soliton source output.
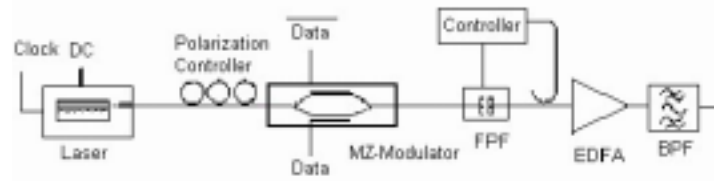
**Figure 13** – Blocks diagram of the soliton source

Due to the light polarization dependence behavior of the $LiNbO_3$ Mach-Zehnder modulator the used of a polarization controller is need, as it is presented in figure 13.
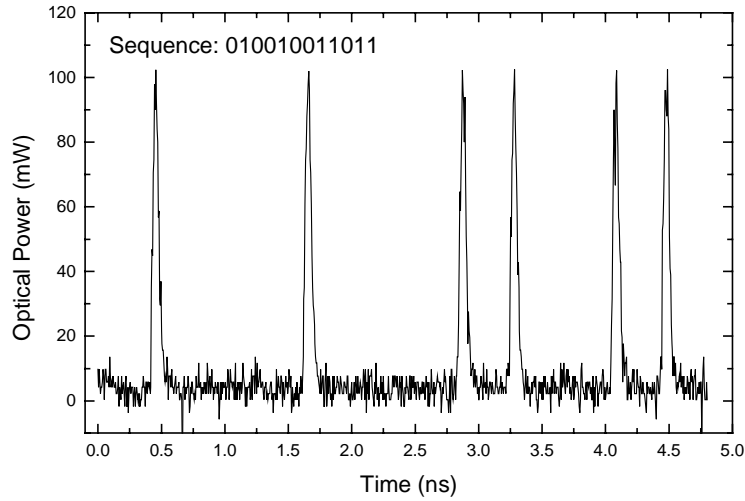
Figure 14 - A pulse modulated sequence measured at the output of the soliton source

The source last stage is composed by an Erbium doped fiber amplifier and an optical filter. The optical amplifier is used to adjust the pulses peak power and the filter, with a 1.6 nm optical bandwidth, removes the amplified spontaneous emission noise introduced by the amplification process out of the signal bandwidth.

With this source we are able to obtain an OSNR of 39 dB, as can be seen in figure 15, with a pulse peak power of 102 mW and an extinction ratio, which is the ratio between the pulses peak power and the optical power level in the logical zeros, of 20.7 dB.
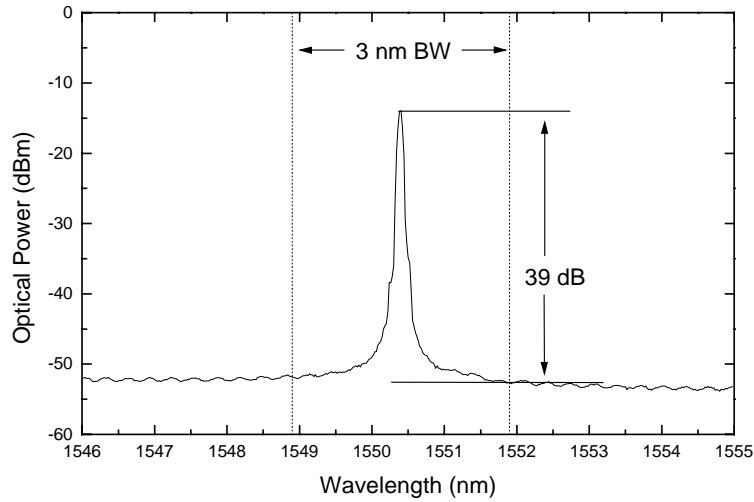
Figure 15 – Optical spectrum at the source output for an optical peak power of 102 mW.

The source was tested in a 45 km 5 channels WDM system available in the laboratory. The setup of the system is present in figure 16.
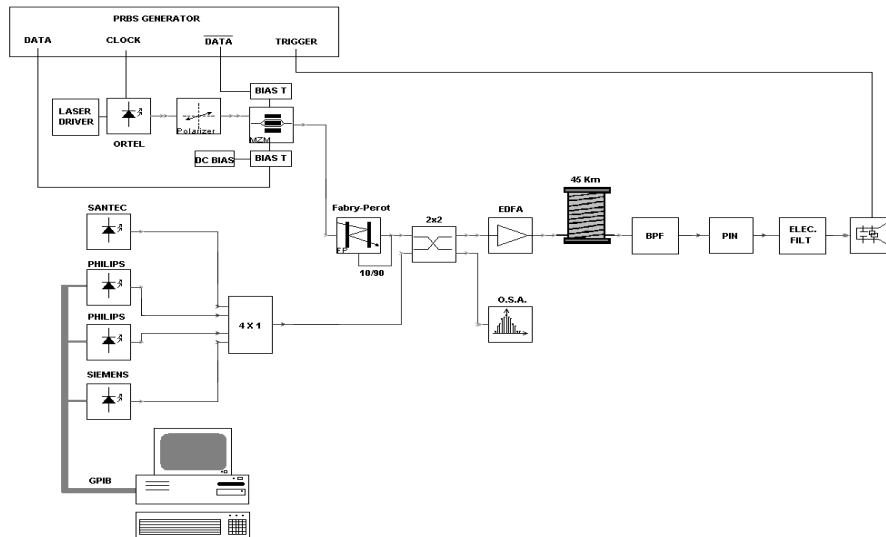
Figure 16 – 45 km 5 channels WDM system used to test the soliton source.

The system has 5 optical channels, one of which is the soliton channel. These 5 optical channels are coupled to a 45 km long single mode standard optical fiber. At the system end, the solitons signal is removed from the WDM signal by means of

optical filtering. The soliton channel is then detected and shaped by an electric filter before the decision circuit. The 5 channels optical spectrum at the fiber input is present in figure 17a and the eye diagram of the detected soliton channel is present in figure 17b.

a)   b)
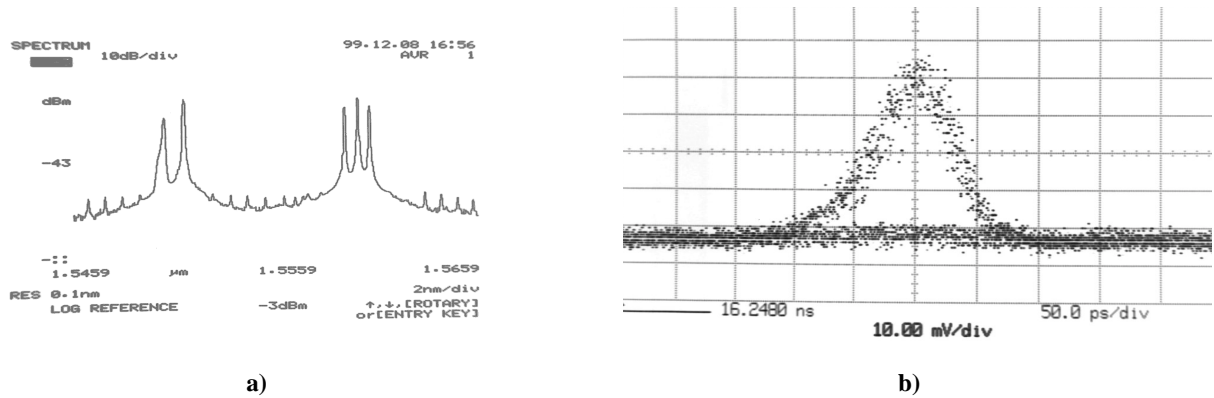
Figure 17 – **a)** Optical spectrum of the 5 channels WDM signal. The soliton channel is the left peak and has a central wavelength of 1550 nm. **b)** Eye diagram of the detected soliton channel.

Even without optimizing the electrical filter, BER values better than 10^{-12} were obtained, proving the stability of this kind of sources for upgrading chromatic dispersion limited single or multi-channels optical systems.

7. CONCLUSIONS

In this work we have shown that by gain-switching it is possible to generate short optical pulses suitable for using in soliton communication systems with bit-rates as high as 10 Gbit/s. We also have shown that using an optical filter we can reduce considerably the frequency chirp, keeping the pulse width as short as 23 ps.

The timing jitter produced by the optical soliton source has a significant impact on the respective communication system performance. In our source, based on a semiconductor laser operating in a gain-switching mode, the main contribution to the timing jitter is the laser noise. Experimentally a standard deviation of 6 ps was measured for the output timing jitter, which is clearly above the uncertainty of the oscilloscope, 1.8 ps, and it is in agreement with simulated results.

The solitons generated by our source were used on a 45 km of standard fiber 5 channels WDM system, with BER values as low as 10^{-12}.

8. ACKNOWLEDGEMENT

9. REFERENCES

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