Characterization and Modelling of Timing Jitter in an Optical Soliton Source Based on a Gain-Switching Semiconductor Laser

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Resumo **– Neste artigo é analisado o jitter temporal à saída de um emissor de solitões baseado na comutação do ganho óptico de um laser semicondutor. Inicialmente é feita uma medição laboratorial do jitter temporal, à saída do laser, posteriormente são identificadas as suas origens. Após a caracterização do ruído do laser semicondutor e do sinal eléctrico usado para pulsar o laser, é desenvolvido um modelo numérico para a simulação. Os resultados obtidos numericamente estão de acordo com as medições laboratoriais.**

Abstract- **In this paper the output timing jitter of a soliton source, based on the gain-switching technique of a semiconductor laser, is analysed. A laboratorial timing jitter measurement, at the laser output, is initially performed, followed by the identification of its origins. After characterizing the laser noise and the electrical signal, used to pulsate the laser, a numerical model is developed in order to be used in the simulation. The numerical results exhibit good agreement with laboratorial ones.**

I. INTRODUCTION

In high speed optical communication systems a technique based in solitons propagation can be used in order to compensate simultaneously the dispersion and the self-phase modulation non-linear effect. Solitons are optical pulses where the evolving of the electric field assumes the hyperbolic secant shape, with a few miliwatt of peak power.

In transmission systems based on solitons several limitations arise when we intend to increase the bit rate. One of such limitations is the temporal uncertainty of the pulses arrival time, usually called timing jitter. As the tolerance of a system to the varying arrival time of the pulses is limited, the timing jitter can be directly related with the system error probability. In this work we will focus our attention in the jitter introduced by the soliton source when it is used a technique based on the gain-switching of a semiconductor laser.

First of all it is characterized the optical soliton emitter used in this study. The laboratorial results of the timing jitter measurements at the output of the semiconductor laser are then presented and analysed. An analytical model, which relates the timing jitter with the spontaneous emission process is then depicted and used in the SCORE[1] simulation environment. The study makes clear the output timing jitter origins in a soliton emitter based on a semiconductor laser gain-switching technique.

II. OPTICAL SOLITON EMITTER

The soliton emitter used on this study is based on a distributed feedback laser (DFB) with an electrical bandwidth greater than 10 GHz, emitting on the 1550 nm window. In order to obtain short optical pulses one can operate the laser in the mode-locked or gain-switching regime [2]. In our soliton source, the DFB laser is operated in the gain-switching regime. This regime consists in the fast commutation of the laser from a low to a higher density of carriers [3]. When the laser drive current is below threshold both carrier and photon density have low values. After the current commutation the carrier density rapidly increases, whereas the photon density increases slowly due to spontaneous emission. At a level above threshold, where the stimulated emission dominates, the optical gain in the laser cavity becomes larger and the photon density rapidly increases causing laser saturation and the appearance of relaxation oscillations. If the current commutes to a level below threshold before the second relaxation oscillation, as it is shown in figure 1, a sequence of narrow optical pulses can be produced.

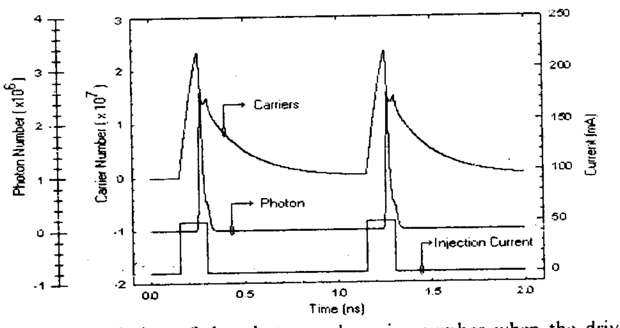

Fig. 1 – Evolution of the photon and carrier number when the drive current forces the laser to commute before the second relaxation oscillation.

In the laboratorial test, the signal used to drive the laser was a clock signal with a nearly sinusoidal shape, but can be used in a similar way to the square signal showed in figure 1.

The direct modulation of the DFB laser using a 2,5 GHz clock signal generates optical pulses with a full width half maximum (FWHM) of 33 ps. The diagram of the soliton emitter can be found in the figure 2.

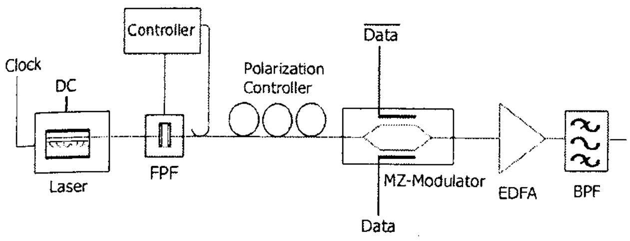

Fig.2 - Diagram of the soliton emitter. The soliton source is achieved through direct modulation of a DFB laser.

A shortcoming of the gain-switching technique 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 fluctuations in the refractive index of the laser cavity induced by the carrier density variations. A 0,16 nm bandwidth Fabry-Perot optical filter is used in order to reduce the mentioned chirp, while the coding section of the emitter is performed by a Mach-Zehnder modulator. The Erbium doped fibre amplifier (EDFA) permits to adjust the pulses peak power. The EDFA is preceded by a 1,16 nm band pass optical filter which removes the spontaneous emission noise, added by the EDFA, that is not in the signal spectral band.

Laboratory measurements showed that the devices in the soliton emitter, see figure 2, that follow the semiconductor laser have negligible contribution to the overall timing jitter, therefore, our jitter analysis is focused into the laser output.

III. MEASUREMENT OF JITTER AT THE SEMICONDUCTOR LASER OUTPUT

The test set used to measure the jitter present at the laser output is depicted in figure 3. An oscilloscope, model HP54120B, was used to obtain an histogram of the time where the electrical pulse detected crosses the imposed threshold.

Figure 4 shows a photograph of the histogram produced by the oscilloscope regarding the time of arrival with respect to the trigger pulses. As the shape of this histogram is approximately gaussian, the jitter can be assumed to have gaussian distribution. Three sets of 10 measurements each were made to determine an average for the jitter standard deviation. The first two sets of measurements were done with two different available optical detectors and the remaining was made in a back-to-back configuration. The results are shown in figure 5.

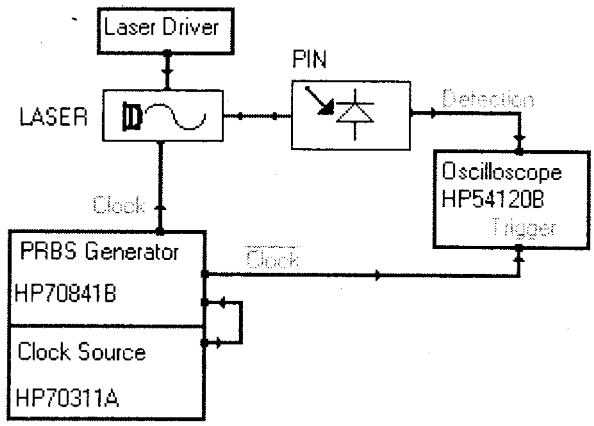

Fig.3 - Test Set for jitter measurements on the soliton source output.

One of the detectors was a direct detection PIN, model HP83440C, while the other was an amplified PIN model HP11982A. The clock generator used was a HP70842B.

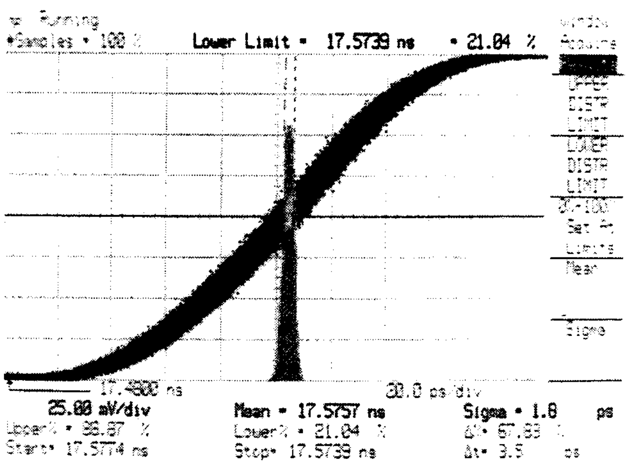

Fig.4 - Photograph of an histogram of a temporal portion of an eye diagram obtained on the oscilloscope. The signal being analysed is the clock signal.

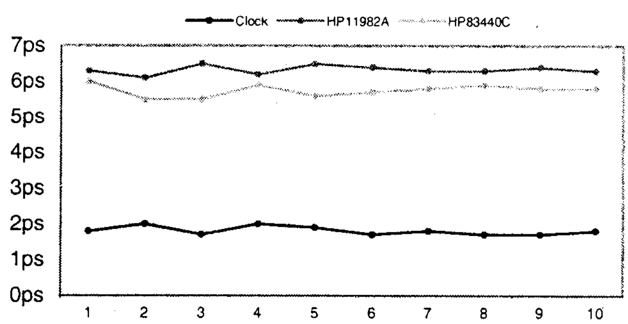

Fig.5 - Three sets of 10 jitter measurements made in the laboratory.

The average in each set of 10 measurements of the jitter standard deviation is 5,75 ps for the HP83440C, 6,33 ps for the HP11982A detector and 1,81 ps for the signal 'Clock'.

IV. JITTER CAUSES

Several phenomena can contribute to the jitter at the laser output as we will point out.

A - The Electrical Clock Signal

The first contribution to the output jitter comes from the electrical signal that modulates the laser, since it comes from a non-ideal clock generator.

If we assume that the frequency noise is white and gaussian with null average, which means to consider a Lorentzian spectral lineshape, then the phase drift in τ seconds has a variance of [4]

$$\sigma^2_{\Delta\phi,\tau} = 2\pi \cdot \Delta\nu \cdot |\tau| \qquad (1)$$

where $\Delta\nu$ is the full linewidth half maximum of the clock spectral density.

The time deviation can be related with the phase drift by

$$\Delta\phi = \frac{2\pi}{T} \cdot \Delta t \qquad (2)$$

where T is the clock period. Assuming τ equals T and using (2) then the standard deviation timing jitter is given by expression (3).

$$\sigma_{\Delta t} = \sqrt{\frac{\Delta\nu \cdot T^3}{2\pi}} \qquad (3)$$

By inspection of the signal on a spectral analyser, model HP8563A, and the expression (3), we have concluded that the jitter produced by the clock generator (signal 'Clock') is negligible, as it falls below a few fentoseconds. Figure 6 shows a photograph taken from the measurement on the spectrum analyser, where is obvious that the linewidth of the fundamental harmonic is as little as the minimum resolution bandwidth supported, 10Hz.

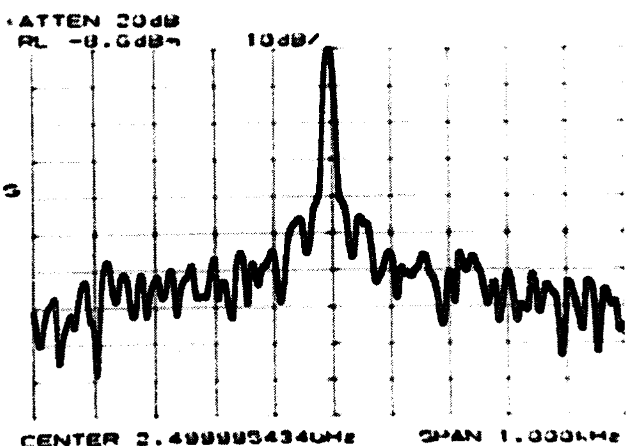

Fig.6 - Photograph of the spectral linewidth of the signal Clock.

B – The Laser Noise

The dynamics of a semiconductor laser can be modelled by the following rate equations [4]:

$$\frac{dN(t)}{dt} = \frac{I(t)}{qV_a} - g(t)S(t) - \frac{N(t)}{\tau_n} + f_n(t) \qquad (4)$$

$$\frac{dS(t)}{dt} = \Gamma g(t)S(t) - \frac{S(t)}{\tau_p} + \frac{\Gamma\beta_s N(t)}{\tau_n} + f_s(t) \qquad (5)$$

$$\frac{d\phi(t)}{dt} = \frac{\alpha_H}{2}\Gamma g_0[N(t) - N_t] + f_\phi(t) \qquad (6)$$

where S(t) and N(t) are the photon and carrier density, respectively, $\phi(t)$ is the electric field phase, I(t) is the drive current, g(t) is the spontaneous emission gain and g_0 is its slope constant, τ_n and τ_p are the carrier lifetime and photon lifetime respectively, Γ is the mode confinement factor, β_s is the spontaneous emission factor, q is the electron charge, V_a is the active layer volume, α_H is the linewidth enhancement factor, N_t is the carrier density at transparency, and f_n, f_s and f_ϕ are the Langevin forces that represent the noise.

A second contribution to the output timing jitter arises from the laser spontaneous emission noise. This noise is dependent of the laser spontaneous emission factor, β_s. Therefore a precise determination of the spontaneous emission factor is important to get a good accuracy in the laser noise simulation.

Since the spontaneous emission process is responsible for the intensity noise, we have decided to measure the relative intensity noise (RIN), which is defined by the ratio between the laser noise power density and the optical signal power, in order to determine the spontaneous emission factor.

Defining the spontaneous emission rate, R_{sp}, as it was defined in [5], it can be related to the spectral power density (one-sided) of the RIN by the expression (7). If the minimum RIN is measured after a few meters of fibre, it is reasonable to consider the dispersion parameter, F, null. Hence we can simplify (7) and end up with (8).

$$RIN(f)/\Delta f = \frac{4Rsp}{Spo}\left(\frac{\sin^2(\omega^2 F)}{\omega^2}(\alpha^2 \,|\, H(j\omega)|^2 + 1) + \frac{\omega^2 + \gamma_n^2}{\omega_r^4}|H(j\omega)|^2 \cos^2(\omega^2 F) - \frac{\alpha \sin^2(2\omega^2 F)}{\omega_r^2}|H(j\omega)|^2\right) \qquad (7)$$

$$RIN(f)/\Delta f = \frac{4R_{sp}}{S_{po}}\left(\frac{\omega^2 + \gamma_n^2}{\omega_r^4}|H(j\omega)|^2\right) \qquad (8)$$

Considering the small signal transfer function, H(jω), obtained by (4), (5) and (6) [4], and replacing it in (8) we obtained (9).

$$R_{sp} = \frac{RIN(f)/\Delta f * S_{po}}{4} * \frac{(\omega_r^2 - \omega^2)^2 + (\omega 2\gamma_r)^2}{(\omega^2 + \gamma_n^2)} \quad (9)$$

were the values of the γ_r (damping carrier factor), $2\gamma_r$ (damping factor of the angular relaxation oscillating frequency), and ω_r^2 (angular relaxation oscillating frequency), are given by the expressions (10), (11) and (12) respectively [4].

$$\gamma_n = \frac{g_{po}S_{po}}{1+\varepsilon_p S_{po}} + \frac{1}{\tau_n} \quad (10)$$

$$2\gamma_r = \frac{g_{po}S_{po}}{1+\varepsilon_p S_{po}}\left(1+\frac{\varepsilon_p}{\tau_p g_{po}}\right) + \frac{1}{\tau_n} \quad (11)$$

$$\omega_r^2 = \frac{g_{po}S_{po}}{\tau_p(1+\varepsilon_p S_{po})}\left(1+\frac{\varepsilon_p}{\tau_p g_{po}}\right) \quad (12)$$

Finally, Rsp is related to the spontaneous emission factor, β_s, by expression (13) [4].

$$R_{sp} \equiv \frac{\beta_s \cdot N_{po}}{\tau_n} \quad (13)$$

If we substitute the steady-state value of the carrier density (Npo), the spontaneous emission factor can be described by (14).

$$\beta_s = \frac{R_{sp}\cdot\tau_p\cdot q}{R_{sp}\cdot\tau_p\cdot q + I_0\cdot\tau_p - S_{po}\cdot q} \quad (14)$$

With expression (14) it is possible to calculate the spontaneous emission factor, from the RIN spectral density, used to determine the spontaneous emission rate parameter, see expression (9), and the other laser parameters. Those laser parameters were extracted during EMITON project, as presented in [6].

Our approach in RIN measurement, was divided in two steps. The first step consisted on finding the maximum of the noise power, when the laser is driven by a direct current just above the threshold, in order to obtain better laser noise measurement accuracy.

This maximum was found in the vicinity of 5 GHz. This maximum noise level is extremely low and demands for alternative methods, as averaging measurement, and the use of an optical receiver with post-amplification. The number of averages taken was 100, and the optical receiver used, one HP11982A, makes the receptor responsivity equivalent to 50 A/W. Figure 7 shows a photograph of the averaged spectrum of the laser noise. A second step is required to determine the carrier continuous wave (CCW) power.

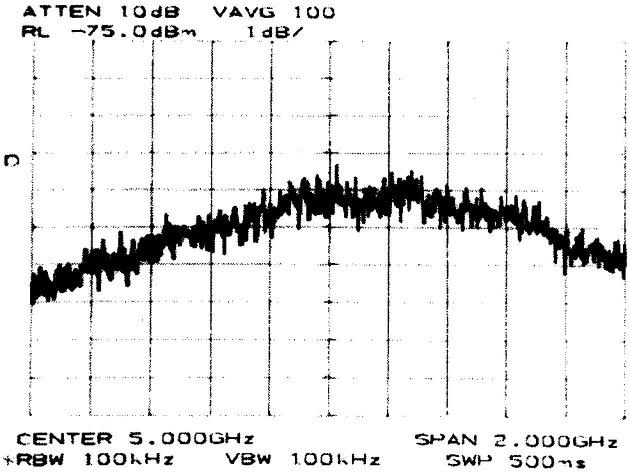

Fig.7 - Photograph of the spectral averaged measurements of the laser noise.

Using an optical multimeter the CCW power was found to be –5 dBm. The maximum value of RIN obtained was -124 dB/Hz, which occurs at a frequency of 5,245 GHz. The β_s was calculated by means of expression (9) and expression (14), using a least minimum square fitting method with 10 points around the maximum noise value. The value obtained was $3{,}58\times10^{-5}$. This parameter, β_s, is a key factor in terms of laser noise simulation accuracy.

We performed the simulation of the soliton emitter, considering this value for β_s, and we obtained numerically a standard deviation timing jitter value of 4,29 ps, that compares with the value of 5,75 ps obtained in the laboratory measurements. From this results we can conclude that the laser noise is the most relevant factor in terms of timing jitter in our soliton emitter.

C – Other contributions to the timing jitter

The additive noise introduced in the system by the optical detector also increase the timing jitter at the decision time. As the two optical detectors used have different noise levels and frequency response, they introduced different levels of jitter, as can be seen in figure 5. The electrical noise introduced by the HP83440C is less than 324 pA^2/Hz according to the device data-sheet. Performing another simulation considering only the thermal noise in the detector device we obtain a standard deviation timing jitter value in the order of 76 fs, which is negligible compared with the turn-on timing jitter of the source, as we saw in section IV-*B*.

The oscilloscope used to perform the histograms measurements introduced also some error in the measurement process. As explained before, see section III, the jitter of the 'Clock' signal is in the order of fentoseconds, negligible for this study, therefore it was assume to be without jitter. In section III, see figure 4, the signal 'Clock' jitter measurement gives a value of 1,81 ps, which can be interpreted as an oscilloscope systematic error. There is no correlation between the oscilloscope uncertainty and the laser noise, so the value of the timing jitter at the laser output can be determined by means of expression (15).

$$\sigma_{real} = \sqrt{\sigma^2_{Measured} - \sigma^2_{Oscilloscope}} \qquad (15)$$

Considering the laboratory jitter measurement, 5,75 ps, and taking into consideration the oscilloscope measurement error, 1,81 ps, we obtain the value of 5,45 ps for the timing jitter standard deviation at the laser output.

In order to analyse the jitter contribution due to the other components of the soliton emitter, see figure 2, we performed a jitter measurement at the Mach-Zehnder output, obtaining the value of 5,76 ps, which confirms the negligible contribution of coding stage of the emitter. The booster amplifier at the emitter output adds spontaneous emission noise to the signal. This noise is partially filtered by a band pass optical filter (BPF), introducing a negligible contribution in terms of timing jitter measured at the soliton emitter output.

D – Drive current against laser output timing jitter

Laboratorial research measurements were made to find out the relationship between the laser bias current and the laser output timing jitter. The increase of the bias current reduces the timing jitter standard deviation, as it is illustrated is figure 8. However, the increasing of the bias current induces the appearance of the second relaxation oscillation that will raise the width of the optical pulse, as shown in figure 9.

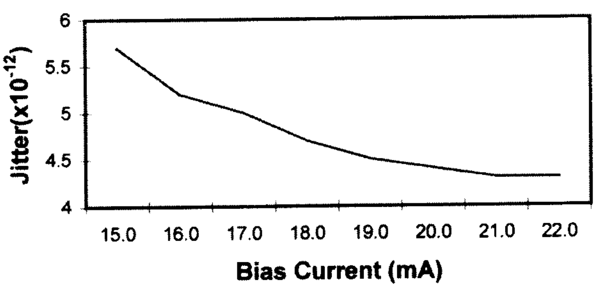

Fig. 8 – Evolution of the timing jitter when the laser drive current increases.

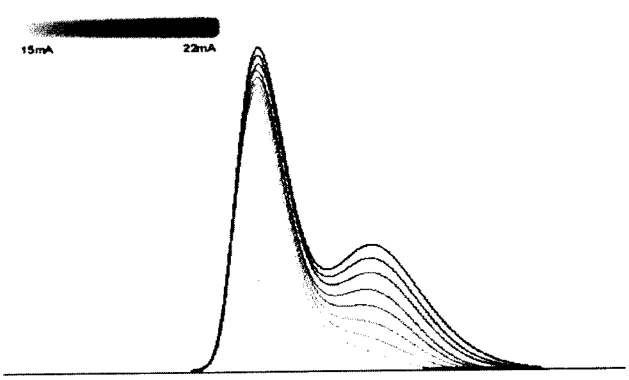

Fig. 9 – Evolution of the optical pulse with the increasing of the laser drive current.

This proves that the laser output timing jitter can be directly controlled by the laser bias current, however the value chosen for this bias current also affects the shape of the optical pulse, which is a significant system performance factor.

V. THEORY

The fluctuations in laser turn-on time delay are a direct result of the dominance of spontaneous emission during times of low photon number in the laser active region, i.e., due to the stochastic nature of spontaneous emission [7].

The output of the laser is separated into two distinct regimes, depending upon the photons number in the active region. In the low number, stochastic regime, the evolution of the photon density is a random process and it can be modelled by a set of modified stochastic laser rate equations. In higher photons number, deterministic regime, the evolution can be modelled by deterministic laser rate equations. In this way, we split the operation of the laser into two regimes: a deterministic regime in which the Langevin noise terms can be negligible and a stochastic regime in which, because of the low photon number the laser is never saturated, the nonlinear gain saturation term can be ignored in (4), (5), (6) and the Langevin terms are significant. Whether or not a laser enters the stochastic regime and the duration it spends in this regime is strongly influenced by the bias current value. As the laser is modulated, its behaviour alternates between the stochastic and deterministic regime.

The work presented in [7], showed that the error rate floors will not be simulated unless it is included the stochastic turn-on process in the laser model. If the stochastic turn-on process is included, the probability density function (PDF) for the delay time, t_d, between the current pulse and the resulting output light pulse, is no longer a deterministic time, but a continuous probability density function. That is why the model of the laser must include the impact of spontaneous emission on the pulses, i.e., the model must include a stochastic component in its description in order to consider in the system's performance analysis the timing jitter due to the soliton emitter.

VI. SIMULATION RESULTS

To simulate the systematic error found on laboratory a model for the 'Clock' signal was developed. The choice of encapsulating the effect of the systematic error caused by the oscilloscope within the 'Clock' model is justified by saying that the contributions of uncorrelated jitters are a commutatively process. The model implementation is obtained by adding gaussian noise and distorting the timeline by means of simple signal-processing techniques, of the sampled signal 'Clock' obtained experimentally. It can be described in the mathematical form of expression (16).

$$G(t)=F(t+\phi(t,\tau))+n(t) \quad (16)$$

F(t) is the sampled Clock, found on laboratory, τ = t\T , where T is the average period, the operator '\' stands for 'integer division', ϕ and n are normal distribution variables.

The overall result of this model is very close to the actual waveform, see figure 10.

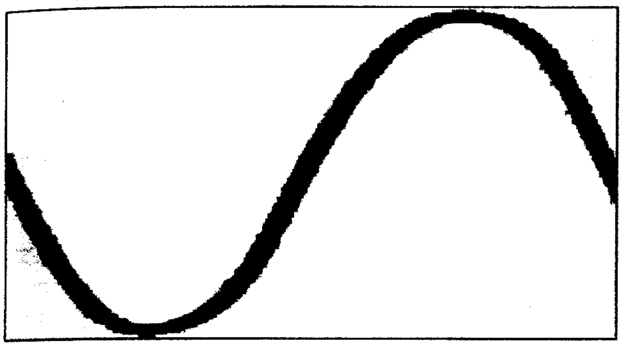

Fig. 10 - Photograph of the signal clock output taken with infinite persistence

The fact that this model, although realistic, presents a rather complex implementation, lead us to make a valid simplification when amplitude fluctuations are not a crucial issue. By suppressing the contribution of ϕ on expression (16), a derived model can be found on the mathematical form of expression (17).

$$G(t)=F(t)+n(t) \quad (17)$$

The results show that the excess of noise needed to simulate the 1,81 ps jitter, creates the latter mentioned fluctuations on peak power, that are not visible on the actual signal. In order to obtained a better accuracy between numerical and laboratorial results the model described by expression (16) was applied.

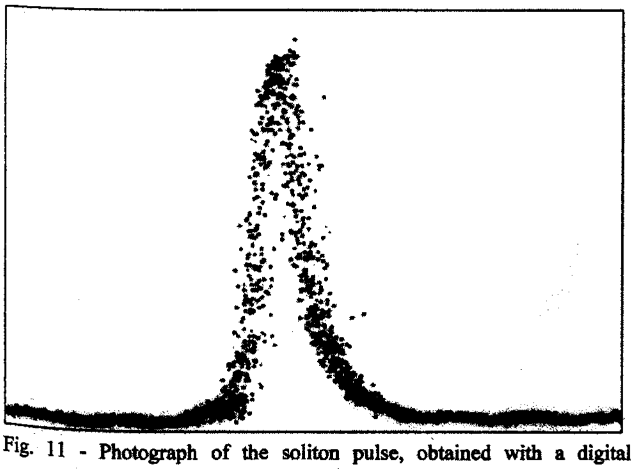

Fig. 11 - Photograph of the soliton pulse, obtained with a digital oscilloscope.

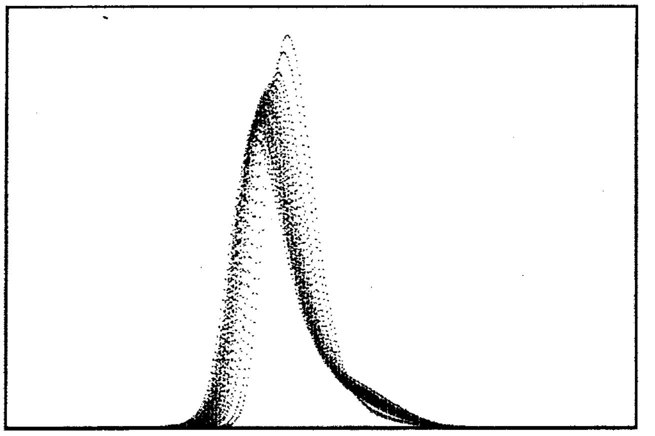

Fig. 12 - Simulated soliton, using the model of expression (16) and considering the laser noise.

The PIN model was numerically implemented through an ideal optical power detector considering the quantum noise by adding a random Poisson process generator. Since the actual PIN, used in the laboratory, has limited bandwidth, a low pass filter was added to the numerical model.

The values for jitter on the clock model are programmable, and were made equal to the uncertainty of the oscilloscope (1,81 ps). When inspecting the spectral components of the signal 'Clock' we have also taken into account the noise-level present. This white noise is responsible for a noise power of –13.9 dBm considering the 20 GHz of the oscilloscope bandwidth. This power corresponds to a variance of 40μW. This variance, was modeled as a gaussian distribution noise source, n(t) in expression (16). The waveform obtained by simulation presents a very high visual likelihood to the detected pulses on laboratory, as shown on figure 13.

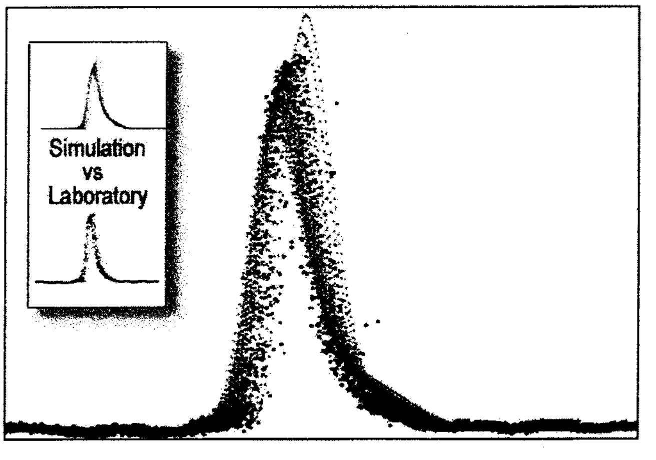

Fig. 13 - The two solitons: Simulation vs. Laboratory superimposed.

In simulation the jitter found on the output of the emitter is 4,29 ps, a value similar to the 5,45 ps measured in the laboratory.

VII. CONCLUSION

The timing jitter produced by the optical soliton emitter can have a significant impact on the respective communication system performance. In our emitter, based on a semiconductor laser operating in a gain-switchig mode, the main contribution to the jitter is due to the laser noise.

The numerical results obtained by simulation exhibit good agreement with laboratorial ones. The jitter found experimentally is 5,45 ps, which is clearly above the systematic error of the oscilloscope, 1,81 ps, and it is in agreement with numerical results, 4,29 ps.

The timing jitter produced by this type of soliton emitter cannot be compensated by additional components in the system. However, it can be partially controlled by an appropriated choice of the laser bias current.

VIII. ACKNOWLEDGMENT

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REFERENCES

[1] R. F. S. Ribeiro, C. J. F. Lourenço and L. F. B. Ribeiro, "Project and Analysis of optical communication systems with SCORE", in *Proc 2nd International Conference on Optical Fiber Submarine Telecommunications Systems* -- Suboptic 93, 29 March 2 April 1993, Versailles - France.

[2] A. Nolasco Pinto, P. S. André, J. L. Pinto, F. da Rocha, "Short optical pulses generation by gain-switching of a DFB laser diode", Confetele'99, Sesimbra, Portugal, Livro de Resumos pp 182, Abril 1999.

[3] Armando N. Pinto, "Análise e Optimização de Sistemas de Comunicação Ópticos Baseados em Solitões", Universidade de Aveiro, 1999.

[4] Rui Ribeiro, "Simulação, Análise e Optimização de Sistemas FSK Ópticos", Universidade de Aveiro, 1996.

[5] K. Peterman e J. Wang, "Small Signal Analysis for Dispersive Optical Fiber Communication Systems", J. of Lightwave Technol., vol. 10, No 1, pp. 96-100, 1992.

[6] Equations Parameters, Proceedings of SPIE, n.º 3572, pp. P. S. André, A. Nolasco Pinto, J. L. Pinto and J. Ferreira da Rocha Extraction of Laser Rate 141-146, 1999.

[7] Tom Stephens, Kerry Hinton, Trevor Anderson and Bruce Clarke, "Laser turn-on delay and chirp noise effects in Gb/s intensity-modulated direct-detection systems", J. of Lightwave Technol., vol. 13, No 4, pp. 666-674, 1995.