Research of the Optical Communications Groups at University of Aveiro and Institute of Telecommunications – Aveiro Pole

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ABSTRACT

This paper summarizes the research activities of the optical communications group at University of Aveiro and Institute of Telecommunications – Aveiro pole. Several activities like clock recovery systems, both electrical and all optical, electrical equalizers for very high bit rate DST systems, post-detection filters for multigigabit optical receivers, soliton systems, simulation work on WDM, DST, EDFA and short pulse generation for high bit rate systems are presented.

Keywords: Clock Recovery, Equalizer, Solitons, WDM, Optical Receivers, Timing Jitter, DST, EDFA.

1. CLOCK RECOVERY UNIT

A clock recovery circuit (CRC), to integrate the receiver unit of a 20 Gsymbol/s optical system, using data formats with no power at the data rate (Binary NRZ and 4-level) was performed. The amplitude of the input signal was 600 mVpp, and was expected an amplitude of approximately 250 mVpp and a jitter inferior to 0.025 UI RMS for the recovered clock signal. Clock recovery circuits can be classified into two groups: open-loop structures and closed-loop or adaptive structures. Although the adaptive approach is preferable, since its phase-lock principle has inherent automatic frequency control capabilities, at very high bit rates the technology needed for a good design and performance of such circuits is not completely mature, and the open-loop solution is preferable[1]. The built open-loop CRU includes a prefilter, a nonlinear circuit (NLC), a high quality factor (Q) bandpass filter and a tuned amplifier (see block diagram in figure1). The prefilter is intended to reshape the incoming signal, in order to reduce the recovered clock jitter. A discrete frequency component at the data rate is generated using a nonlinear circuit. This NLC is an unbalanced square nonlinearity, since such structure is achieved with very simple circuits, and there is only negligible degradation in performance when compared to a balanced nonlinearity, as concluded by Matos *et al*[2]. The high-Q bandpass filter is intended to reduce the noise level associated to the produced discrete component, and at the considered data rate it is implemented using a dielectric resonator (DR) with a quality factor of approximately 750. Finally, the tuned amplifier has three main purposes: to provide the required signal levels, to reduce the degradation caused by the out of band spurious modes of the non-ideal high-Q bandpass filter and also to isolate the CRU from the subsequent units.

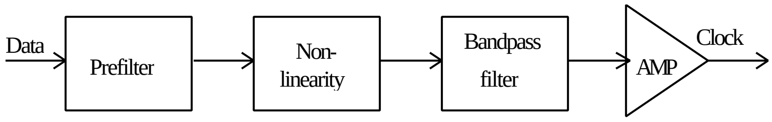


Fig. 1. Block diagram of an open-loop clock recovery unit.

The NLC and the tuned amplifier were integrated in the same GaAs monolithic microwave integrated circuit (MMIC), in order to improve the reliability, performance and to reduce the size and the cost. The circuit has been fabricated at the PML foundry using the D02AH process, which uses 0.2 µm gate length pseudomorphic HEMTs (high-electron-mobility transistors). The nonlinearity input stage performs the necessary signal formatting to reduce the jitter of the recovered clock, avoiding the use of additional pre-filtering. Figure 2 a) presents the circuit mask submitted to the Foundry. The MMIC was mounted on a carrier and bond wires were used to connect it to the external circuits. In figure 2.b) is presented the assembled circuit prototype.

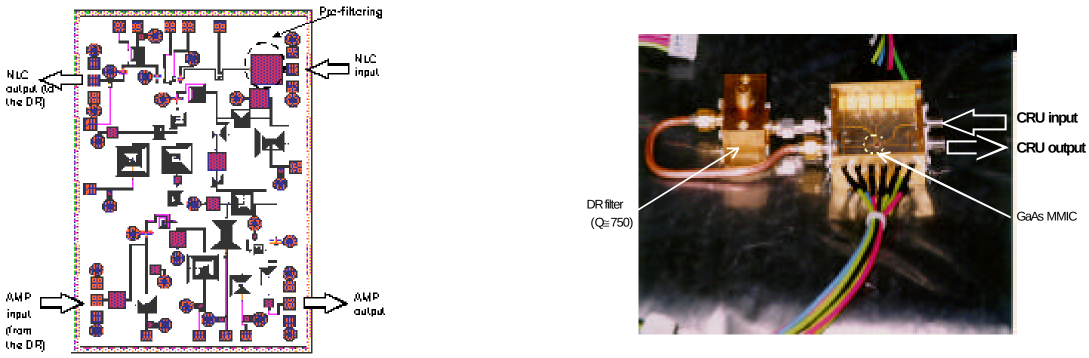
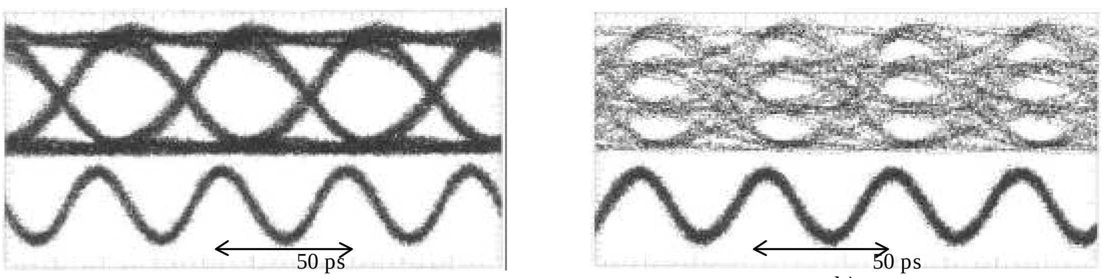


Fig. 2. a) Mask of the MMIC (prefilter, NLC and tuned amplifier) submitted to the Foundry, b) Assembled circuit prototype.

Figure 3 presents the eye-diagrams of the recovered clock signals (bottom) and the input waveforms (up). These input wave forms are 19.90656 Gsymb/s (2*STM-64) PRBS of length 2^{31}-1 symbols and amplitude 600 mVpp, with two different line codings, Binary NRZ (figure 3) and 4-level (figure 3). The measured amplitude and jitter of the clock signal are respectively 200 mVpp and 0.010 UI RMS for the NRZ case, and 140 mVpp and 0.018 UI RMS for the 4-level case, thus satisfying the proposed specifications.



a) *b)*

Fig. 3. Measured eye-diagrams at the input and output of the clock recovery unit considering two different line codings.
a) Binary NRZ. b) Multilevel (4-level).

2. SIMULATION WORK ON WDM

Major changes are occurring in telecommunications. User requirements are shifting towards new services, such as multimedia communications, high definition image transmission, high volume file transfer and others. Due to the high rates involved, such networks will use optical fiber as the transmission medium. It has been widely recognized that a network to provide an adequate level of services will have to provide multiple concurrent connectivity channels between the nodes. This can be accomplished in an optical network through the use of wavelength division multiplexing (WDM), where a different wavelength is allocated to each channel. A large variety of WDM network topologies has been proposed. They employ tunable transmitter and/or receiver at the nodes. In that way the logical network topology becomes independent of the physical network topology, as long as all the nodes have access to all wavelengths.

In the DAWN project it is proposed a new WDM network topology which features the dynamic allocation of wavelengths. This network topology is based on the use of a Reflective Semiconductor Optical Amplifier (RSOA). In the proposed topology, the principal components of a transmitter at each node are a RSOA and a tunable optical filter. The node receives a signal comprising a comb of reference wavelengths and selects one of the wavelengths by appropriately setting the optical filter. The received signal travels along the RSOA where it is amplified, modulated and reflected back to the network. Besides providing gain, this simple scheme has the advantage of facilitating wavelength monitoring and control at the controlling node. At the receiver, by appropriate filtering of the received signal, the data is separated from the signaling information. A control channel is provided by adopting subcarrier multiplexing techniques[3]. The nodes are informed which wavelength is being used to carry the incoming message. The great objective of the project is to develop a demonstrator consisting of four nodes (three user nodes and a controlling node), connected using a passive star topology. The demonstrator will operate in the 1550 nm region and will support 1 Gbit/s data transmission, using direct detection.

3. ELECTRICAL EQUALIZER FOR VERY HIGH BIT RATE DST SYSTEMS

An electrical adjustable equalizer was developed for very high bit rate optical communications systems using the standard single mode fiber (SMF) and based on dispersion supported transmission (DST)[4]. The equalizer was constructed in the framework of the European Community ACTS project SPEED ("Superhighway by Photonically and Electronically Enhanced Digital Transmission"). The main objective of this project is to demonstrate the feasibility of very high bit rate (20 Gbit/s and 40 Gbit/s) optical transmission systems in the transit network, using the electrical time division multiplexing approach. Figure 4 shows the photograph of the DST equalizer and the control and bias circuits. The equalizer was designed using a GaAs monolithic technology and it has the main advantages to be electrically adjustable, a good input and output impedance match and also a small size.

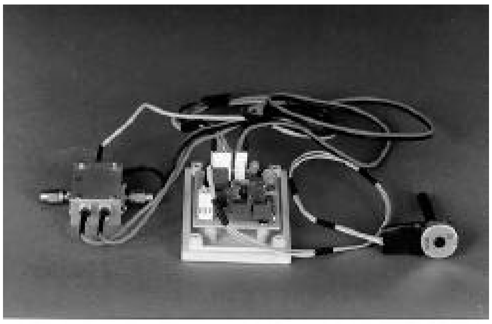


Fig. 4. Photograph of the DST equalizer with control and bias circuits.

By using the electrical equalizer and the DST technique it is possible to transmit 20 Gbit/s, 40 Km, at standard single mode fiber without regenerating repeaters[4]. The achieved product bit rate×distance is well beyond the limit due to the chromatic dispersion.

4. POST-DETECTION FILTERS FOR MULTIGIGABIT OPTICAL RECEIVERS

The post-detection receiver filter has the function to reshape the received signal in order to produce well defined pulse shape with low noise, low intersymbol interference and low telegraph distortion at the input of the decision circuit. A well designed post-detection filter, effecting appropriate pulse shaping, can improve significantly the performance of the optical system. However, there are constraints in filter design: it must be easily fabricated, insensitive to manufacturing tolerances, have a reasonable physical size and must also easily integrate with the other optical receiver components. Different microwave filter design strategies were investigated to be used at receiver units developed for the optical communication system demonstrators of the European Community projects ACTS ("Advanced Communications Technologies and Services"), namely the UPGRADE ("High Bit rate 1300nm Upgrade of the European Standard Single-Mode Fiber Network") and ESTHER ("Exploitation of Soliton Transmission Highways in the European Ring"). Both projects have the principal objectives to demonstrated in field trials and with real traffic the advantages of the return to zero (RZ) transmission systems to upgrade the present infrastructure and/or development new high capacity transport networks. The main difference between the two projects is the wavelength operation, the UPGRADE project develops optical systems for long haul and high bit rates at the second optical window and the ESTHER project develops the systems at the third optical window. Figure 5 shows an example of a passive post-detection filter designed for a 10 Gbit/s RZ optical receiver unit. This passive filter is based on a step impedance microstrip distributed structure and it has the advantages of simplicity and low-cost production. In spite of the good results achieved by using these filters [5,6], it is impossible to adjust their response for different system operating conditions and therefore they must be carefully designed for each particular system.

In order to provide post-detection filters with electrical tunability there were investigated active filter structures[5,7,8]. Figure 6 shows an example of an active filter implement in monolithic technology for 10 Gbit/s optical soliton system. This filter exhibits a good input and output impedance match to avoid the performance degradation due to the back reflections and also a small physical size ($2\times1.5\times0.1$ mm^3) to be easily integrated with the other receiver components.

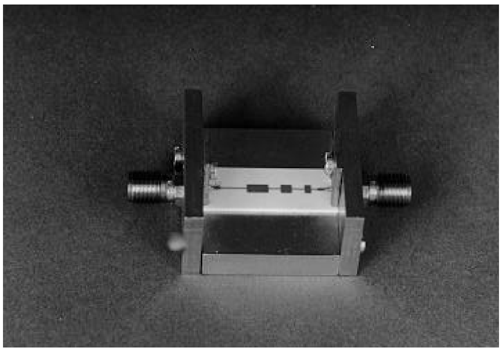


Fig. 5. Microstrip filter prototype mounted in a test carrier.

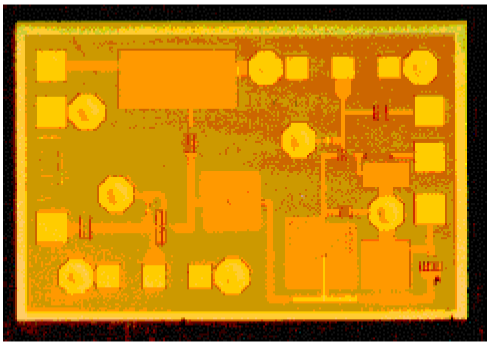


Fig. 6. Photomicrograph of an adjustable post-detection filter with active impedance matching for optical soliton communication systems.

5. SIMULATION WORK IN DST

This work is based on the Dispersion Supported Transmission (DST) accommodation scheme already standardized by the ITU-T recommendation G.691. This scheme is based on the electronic accommodation of the fiber dispersion by equalization. Due to the second order dispersion in standard Single-Mode Fiber (SMF), the transmission of 20Gbit/s binary Non-return to Zero (NRZ) signals, without dispersion compensation, is limited to about 20km[9]. Dispersion Supported Transmission (DST)[10] overcomes the dispersion limit. This scheme makes use of direct modulation of the LASER and a simple equalization scheme[11]. Further improvements can be obtained by using DST with multi-level coding[12,13]. However, to achieve the benefits of this technique, receiver equalizer and laser must be appropriately optimized. The configuration of this kind of systems is similar to any other case, and is presented in figure 7 for a four-level 40Gbit/s case.

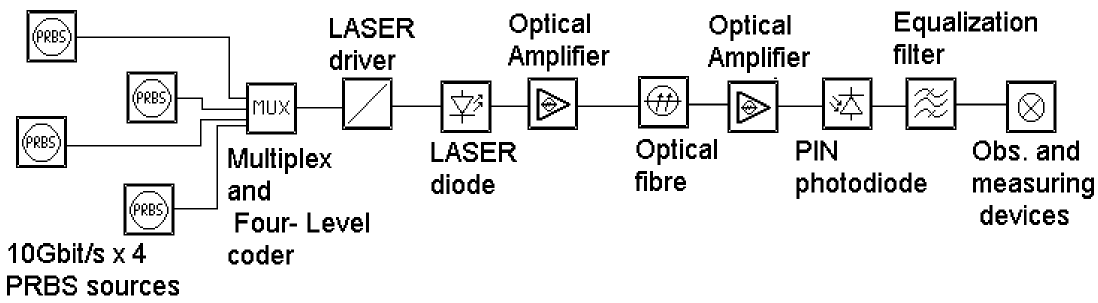


Fig. 7. Simulations set-up for the four level DST 40Gbit/s 46.2 km system.

A DST system is based in the high-pass characteristic of the detected signal, that results from the frequency modulation induced by direct modulation of a diode LASER and the low-pass characteristic of the SMF. The resulting characteristic can be easily equalized for some system parameters (LASER FM efficiency, E_{FM}, and SMF parameters). The Small Signal Transfer Function (SSTF) of a DST system without any equalization can be written has follows[14]:

$$H_s(\omega) = \cos\left(\Phi\omega^2\right) - \alpha \sin\left(\Phi\omega^2\right) + j\alpha\gamma_p \frac{\sin\left(\Phi\omega^2\right)}{\omega} \tag{1}$$

where α is the LASER line-width enhancement factor, γ_p is the small signal decay rate for the photon population:

$$\gamma_p = \left(\varepsilon S_0\right)/\tau_p\ , \quad \Phi = \left(\lambda^2 DL\right)/(4\pi c) \tag{2}$$

In these expressions D is the fiber dispersion parameter, L is the length, S_0 is the photon density at bias point, τ_p is the photon lifetime and ε is the non-linear gain compression factor. In figure 8a), it can be found a graphical representation of this transfer function for a particular system.

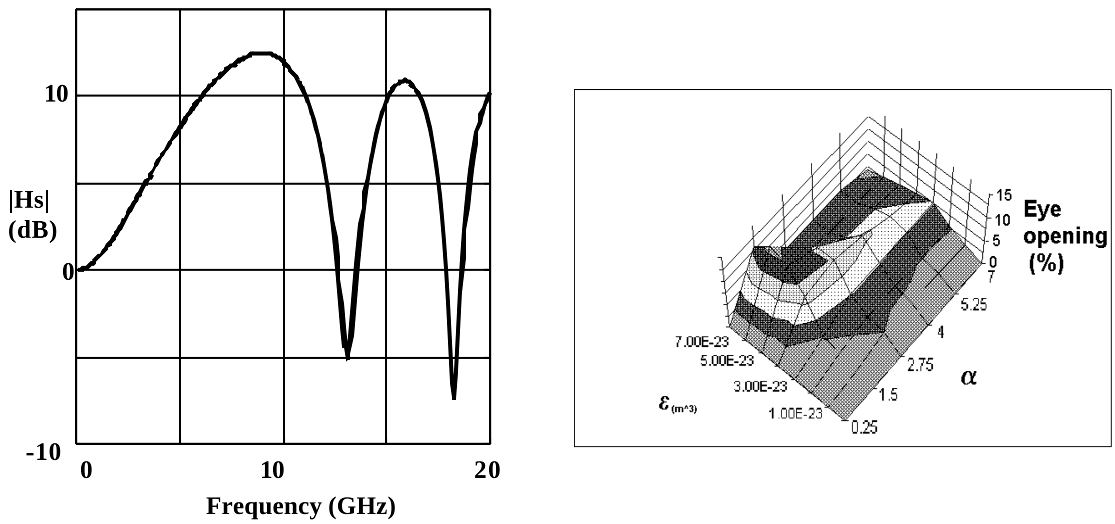


Fig. 8. a) Modulus of the uncompensated system response for α=2.95 and ε=3.8E-23m3

b) Eye opening as a function of α and ε when the LASER noise is considered

The parameters that seem suitable of optimization since are simultaneously related to the FM efficiency (E_{FM}) and to the SSTF are the line-width enhancement factor (α) and the NLGC (ε).Figure 8b) shows an evaluation of the system performance based on the change of the referred parameters of the laser[15]. The performance assessment was made based on an average of the three eyes opening. As it can be observed there a particular point where the performance of the system is optimum. In any case all other parameters are optimized for each obtained point. Other step needed for the best performance of the system is to get the best optimization scheme possible. The work led us to the use of a pole-zero configuration of the receiver equalizer. The need for this flexibility comes from the fact that there are several types of laser that can be used for transmitting DST. The pole frequency can be obtained simply by[16], but in practice there must be made some little tuning. It was then suggested another formulation[17]:

$$f_c = \frac{m\, f_w}{\sqrt[4]{1 - 8p^2 maF\ f_w^{\ 2}}}\ , \quad f_w = \frac{1}{2pkF}\ , \quad k = 4pE_{FM}\left(I_0 - I_{th}\right) \tag{3}$$

Where m is a power index (normally set to one), E_{FM} is the FM efficiency, $I_{0,th}$ are the bias and the threshold current of the laser respectively and the remaining parameters were already defined. With respect to the zero, this is only needed in some cases, as shown in figure 9. The flat zone represents the range where the zero is almost not noticed. This work has been partly supported by the Portuguese program PRAXIS XXI and the European Commission in the project AC049 "SPEED".

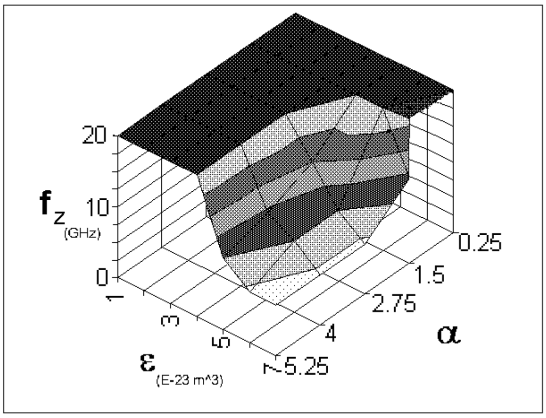


Fig. 9. Equalizer zero frequency as a function of the α and the ε of the LASER

6. SOLITON TRANSMISSION MODELLING

The objectives of this work were to explore several scenarios where the solitons can be transmitted and exploit the several mechanisms of control and modulation of this kind of pulses. Among the contributions of the University, there was the exploitation of the possibilities of the system expandability to WDM (Wavelength-Division Multiplexing). Several systems were modeled and simulated in order to obtain the limits in this kind of expansion. The study of the several types of control and propagation methods was made in order to have one idea of the kinds of problems that could happen in the several types of systems. The systems that had to be studied were various and recurred to Polarization multiplexing in the same channel to reduce interaction, to filtering[18] and to dispersion management[19]. In order to consider the upgradability of these kind of systems, many phenomena had to be considered: Polarization Mode Dispersion[23]; average solitons behavior[20]; soliton to soliton interaction within the same channel and between multiple channels [21]; dispersion management effects on solitons and gaussian pulses and effects of this on the propagation and interaction in WDM systems [22,24].For the particular systems studied, the results shown that for step index fibers and for the systems characterized there was a minimum separation in the order of the nanometers due to the soliton interaction among the different channels. This fact limited the number of channels possible in the Erbium Bandwidth to about 5x10Gbit/s and to distances in the order of 300km with amplifier spacing of 50km. In the case of the dispersion management (DM) with step index fibers the limit was not so evident in the distance due to the advantages of the DM technique we could reach up to 20x10Gbit/s channels in the EDFA band up to 1000km with 100km amplifier spacing. With the dispersion shifted fiber, 20x20Gbit/s without Polarization multiplexing could be achieved up to more than 1000km. With polarization multiplexing the systems could be expanded to 600Gbit/s over distances up to 1000km with amplifiers spacing of about 100km. In the system with filtering the distance was 600km and the total bit rate was of 41x10Gbit/s. This work was sponsored by the European project ESTHER- Exploitation of soliton transmission Highways in the European Ring, that aimed to transmit solitons over the already installed links of fiber.

7. OPTICAL SOLITON SOURCE

Soliton transmission has been appreciated as a possible and easy way to obtain high bit rates in long distance communication systems. Our research was focused on the transmission experiments, which exploited solitons sources suitable for use outside the laboratory. Our soliton source is based on a DFB laser with a bandwidth greater than 10 GHz emitting on the 1550 nm window. To obtain sort optical impulses is necessary to operate the laser in the mode-locked or in the gain-switching regime [25,26]. We operate our laser in a non-linear regime of gain switching. In these conditions with a modulation sinusoidal signal of 2.5 GHz is obtained an optical pulse with a width of 20 ps[27], the diagram of the soliton source can be found in the figure 10.

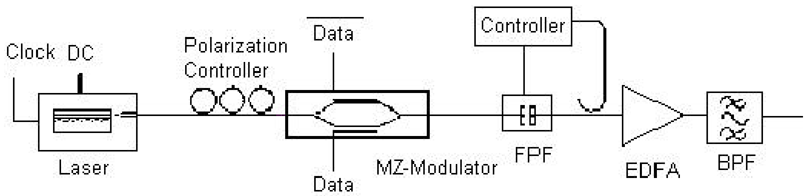
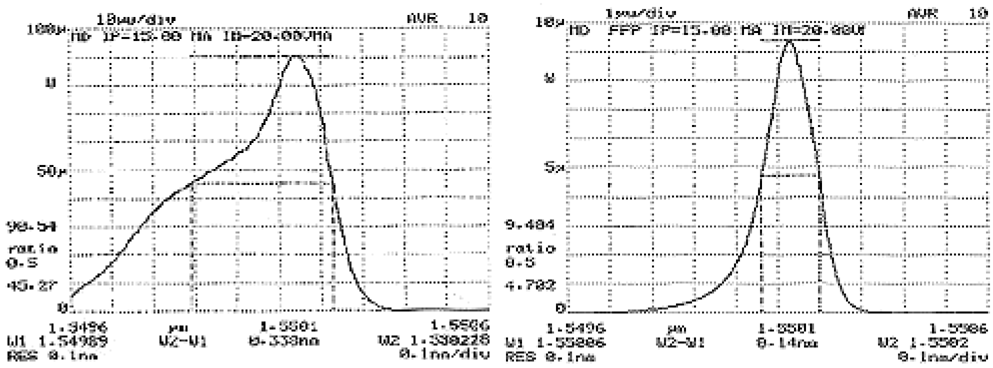


Fig. 10. Diagram of the optical source.

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. The optical frequency chirp produces a considerable broadening in the pulse spectrum that is translated into a time broadening after fiber propagation due to the chromatic dispersion. For a 20 ps soliton width we should expect a spectrum width of about 11 GHz, around the laser central frequency. However, as we can see in figure 11-(a), we measured a spectrum width of about 34 GHz in the laboratory. Besides that for a chirp free soliton, we should expect a symmetric secant hyperbolic spectrum shape. The spectrum presented in figure 11-(a) is way from a symmetric spectrum and we clearly see the broadening of the left side due to the frequency chirp.



(a) (b)

Fig. 11. Before the optical filter, (a), the pulse present a spectral width of 34 GHz, after the optical filter (b) the spectral width was reduced by a factor of 2. Besides that the soliton time width remains practically unchangeable

In order to reduce the frequency chirp we tried to filter the pulse with a narrow optical filter. We used a Fabry-Perot filter with a bandwidth of 0.16 nm, and as we can see in figure 11-(b), the filter considerably reduces the pulse spectrum. The optical filter also produces some effect in the pulse time domain. However, this effect is small. We measured a pulse width after the filter of about 23 ps, which is suitable for a 10 Gbit/s soliton system[28]. Another important feature of the soliton source is the ability to block the pulses according to data, we studied the different modulation techniques with application in high bit rate communication systems. The chosen technique was the use of a Mach-Zhender interferometer to codify the generated pulses with the data sequence.

8. OPTICAL COMUNICATION SYSTEMS BASEAD IN SOLITONS

Most of the previous attempts to evaluate the BER of solitons systems were made under the assumption that the critical effect is the signal-to-noise ratio (S/N), following the same approach used for BER evaluation in non return to zero (NRZ) systems. However, in soliton systems the timing jitter can be the dominant effect, mainly due to soliton-to-soliton interactions and spontaneous emission noise. Following a previous work[29], where we developed a non-Gaussian timing jitter model, which takes into account the Gordon-Haus effect and the solitons interaction, we are studying a detailed description of the soliton receiver considering the timing jitter. We are using several results from a laboratory system, based on our soliton source, see figure 12, to compare the analytical work with experimental data [30].

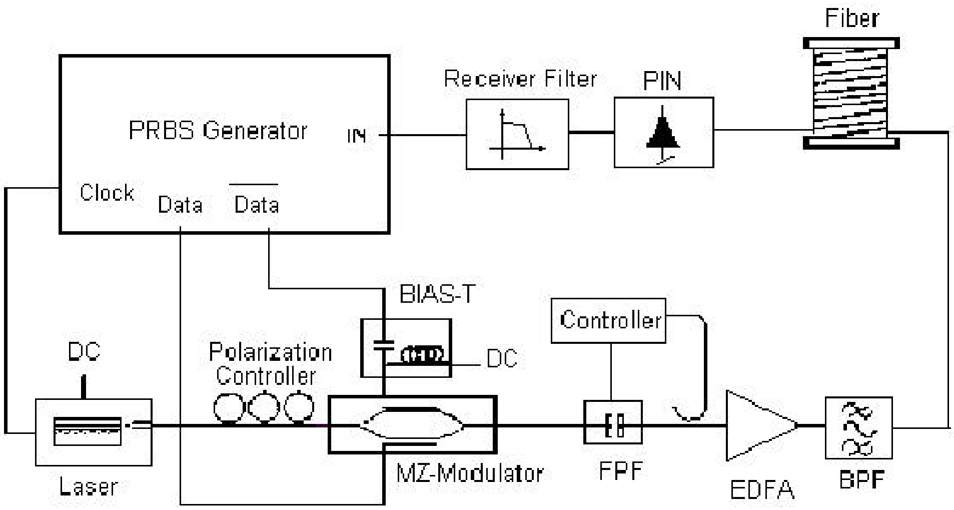


Fig. 12. Laboratory system used for experimental BER evaluation

We are also working in system components characterization in order to obtain precise simulation results. We already performed a full soliton source characterization[31] and we obtained accurate simulation results for both the envelope and frequency of the optical field, as we can see in figure 13.

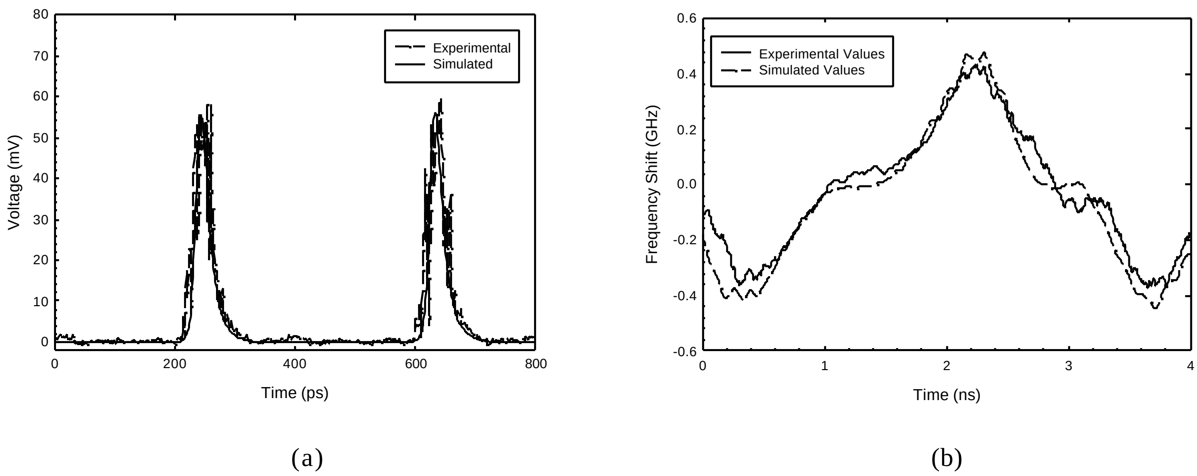


Fig. 13. Envelope (a) and frequency (b) of the optical field. We present the measurement made in the laboratory and the result of numerical simulation.

9. SIMULATION AND EXPERIMENTAL WORK ON ALL OPTICAL CLOCK RECOVERY

Optical clock recovery, using the injection locking mechanism, was investigated. The main goal was to evaluate the performance of this mechanism to produce a 10GHz optical clock suitable for demultiplexing a 4x10 Gbps input data stream. The study was based in the sustained pulsation conditions in a single cavity semiconductor laser according to the Lang model[32]. The influence of the external light injection level, detuning and increasing step height of the excitation bias current were taken into account in this study. For the simulation of the clock extraction process, we have considered a 10Gbps data stream obtained by modulating in amplitude a CW laser. The optical stream is combined with three delayed copies to generate a pseudo 40Gbps sequence. It was found that a 10 GHz self-sustained pulsation can be achieved if the injected light level on the laser is increased significantly and the bias current is reduced. This means that the system can operate in a reasonable bias current range if a higher level of injected light can be guaranteed[33]. After we have achieved 10 GHz self-sustained pulsation an input data sequence is injected in the device. It is important to evaluate the system performance when the data stream consists of random sets of 0's and 1's. The main aspect is the lock-in range of the optical clock. This can be assessed by looking at the phase drift dynamics when receiving long sequences of 0's. From the simulations it was concluded that the injection locking mechanism may be used with success in all-optical clock recovery. It was seen that the clock extractor will be more stable for higher values of the relative excitation. However if the laser can not be driven with high currents than a reasonable level of injected light must be assured. The phase synchronism can be guaranteed if the self-pulsation frequency is near to 10 GHz.

The experimental set-up (see figure 14) was built using one Multiple Quantum-Well (MQW) distributed feedback (DFB) semiconductor laser. The device operates at 1310nm, having an active length of 250µm and a threshold current of I_{th}=11.2 mA @ 25ºC. One facet is AR-coated and the other has 30% reflectivity. The light from the AR-coated facet is collected with an optical ferrule and from the other side with a lensed fiber taper. Both collecting devices are mounted on XYZ micro positioning systems. The optical amplifier has 7.8 dB of gain and optical filters were tuned to allow through only the correct wavelength (1310nm). The input signal is soliton type RZ signal with 5dBm of average power and a 3ps of FWHM at 10Gbps. It was observed that the system is very sensitive to light polarization. With this configuration the frequency of self pulsation can be modified simply adjusting the bias current[34]. For lower currents it was verified that the self pulsation frequency is near 6 GHz and the device is stable. For higher currents the self pulsation frequency increases to near 11GHz. Figure 15 shows results of optical synchronization with an input data stream at 10GHz.

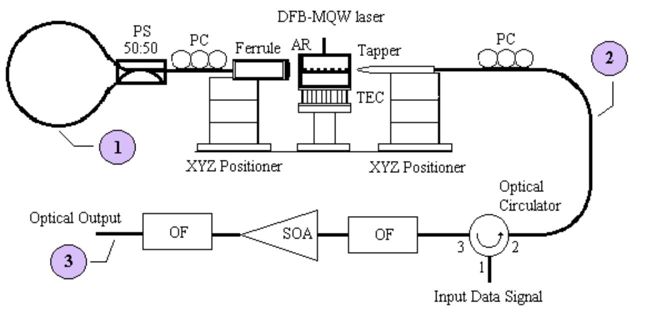


Fig. 14 . Experimental Set-up

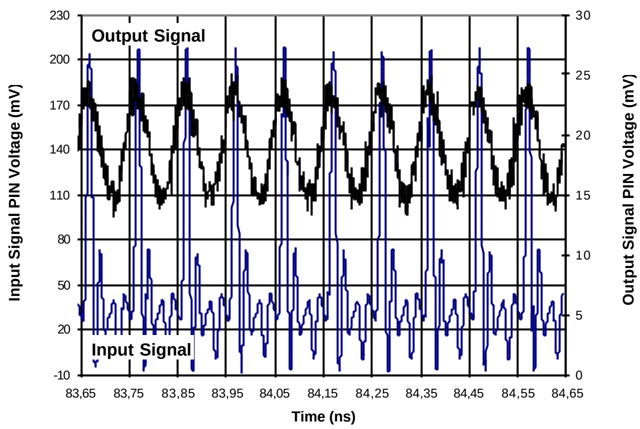


Fig. 15. Laser synchronization with a all ones input sequence

10. EDFA IMPACT ON IM-DD OPTICAL COMMUNICATION SYSTEMS

This project intended to assess the actual impact of optical pre-amplification, e.g. by an EDFA, on the performance of optical receivers. The more accurate existing methodologies involved the use of Moment Generating Functions in bounds for the bit-error rate. The challenge was then to develop new or the same bounds with a new and trusted Moment Generating Function (MGF) taking into account the noise sources and stochastic processes occurring in the optical domain, due to amplification. As a consequence, an experimental prototype was actually built from scratch, including the control and interface electronics as well as software. The project was partially sponsored by JNICT-Portuguese Office for Scientific & Technological Research, and the European Community under the RACE project (EU-R2001).

The MGF of the detected fotocurrent in a PIN diode receiver was analytically derived[35] yielding,

$$M_Y(s)=\frac{\exp\left\{\int_{-\infty}^{\infty}\left[\frac{\mathrm{R}\left(\mathrm{e}xp\left[s\,\mathrm{qh_r}(\mathrm{t}-t)\right]-1\right)Gh_p(t)}{1-\mathrm{R}\,N_0\left(\mathrm{e}xp\left[s\,\mathrm{qh_r}(\mathrm{t}-t)\right]-1\right)}\right]\mathrm{d}\,t\right\}}{\exp\left\{\int_{-\infty}^{\infty}B_0\,.\ln\left[1-RN_0\left(\mathrm{e}\,xp\left[s\,\mathrm{qh_r}(\mathrm{t}-t)\right]-1\right)\right]\mathrm{d}\,t\right\}} \tag{4}$$

This simple formula is valid for a single bit coded by an optical power pulse of shape $h_p(t)$, non-ideally amplified with gain G, additive noise of power spectral density N_0 band-filtered over a width B_0. R.q is the detector responsivity, being q the electron charge and $h_r(t)$ is the electrical post-detection filter impulse response. To consider Intersymbol Interference (with n-relevant neighbour bits) and Gaussian additive noise of the receiver Front-end, the MGF must be extended. Then for a decision about the symbol a_0=”0”, the MGF of the random variable Y defined as the detected fotocurrent at the actual decision instant, is given by

$$M_{Y_0}(s,t)=\frac{1}{C(s,t).2^{2n}}.\prod_{\substack{-n\\k\neq 0}}^{n}\left[1+\exp\left\{\int_{-\infty}^{\infty}\frac{F(s,t,t)}{N(s,t,t)}.h_p(t-kT)\,\mathrm{d}\,t\right\}\right] \tag{5}$$

where

$$F(s,t,t)=G\,\mathrm{R}\left(\mathrm{e}^{\mathrm{sqh_r}(\mathrm{t}-t)}-1\right);\quad N(s,t,t)=1-\mathrm{R}\,N_o\left(\mathrm{e}^{\mathrm{sqh_r}(\mathrm{t}-t)}-1\right) \tag{6}$$

$$C(s,t)=\exp\left\{\int_{-\infty}^{\infty}B_o\,.\ln\left[1-RN_o\left(\mathrm{e}^{\mathrm{sqh_r}(\mathrm{t}-t)}-1\right)\right]\mathrm{d}\,t\right\}; \tag{7}$$

With a similar proceeding, the conditioned MGF for symbol a_0=”1” is found as

$$M_{Y_1}(s,t)=M_{Y_0}(s,t).\exp\left\{\int_{-\infty}^{\infty}\frac{F(s,t,t)}{N(s,t,t)}.h_p(t)\,\mathrm{d}\,t\right\}; \tag{8}$$

Finally, the Gaussian additive noise is easily accounted, as it benefits of statistical independence of any other stochastic process, assuming its variance s_{pre}^{2} is known. The complete process is represented by the random variable Z and its MGF can be derived from the MGF of Y, yielding

$$M_{Z_j}(s,t)=M_{Y_j}(s,t).M_{pre}(s),\quad \mathrm{j=0,1} \tag{9}$$

Index j stands for the binary symbol “0” or “1” actually sent by the transmitter. For Gaussian noise, one has

$$M_{pre}(s)=\exp\left\{\frac{s_{pre}^{2}.s^{2}}{2}\right\} \tag{10}$$

The new model has overcome some inconsistencies of previous formulations with physical results like the different variance terms. In particular, the formulation is also consistent with widely recognized Yamamoto[36] and Personick[37]. In order to further prove this result, simulation work was performed and an EDFA prototype has been built. This prototype included a 980 nm pump laser, a wide optical filter and full electronic circuitry needed for control and interface. In either case the new formulations for the behavior of the system have been verified as long as B_0 significantly exceeded the electrical signal bandwidth.

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