GENERATION AND PROPAGATION OF SHORT PULSES IN THE 1.3 μm OPTICAL COMMUNICATION WINDOW

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Resumo: Apresenta-se um estudo experimental sobre geração de pulsos curtos utilizando laser a fibra de fluoreto dopada com praseodímio (com *mode-locking)* e laser semicondutor DFB com chaveamento de ganho. Os lasers a fibra utilizaram um modulação de fase ou uma modulação cruzada de fase (XPM) para obter o *mode-locking*. No primeiro caso, utilizou-se um diodo laser de 1,55 μm com chaveamento de ganho para modular a fase do laser de 1,3 μm via XPM intracavidade; isto produziu pulsos de 50 ps e 13 mW em 2,8 Ghz. No segundo laser observou-se também puslos escuros estáveis com duração de 140 a 200 ps, tornando este laser atrativo como gerador de sólitons escuros. No caso de diodo laser com chaveamento de ganho, após uma filtragem espectral, obteve-se pulsos de 5 ps, 20 mW em 1 Ghz. Usando este laser com chaveamento de ganho, foi feita a propagação de sólitons por 50 km em fibra óptica convencional, demonstrando, desta forma, seu potencial como fonte laser simples e barata para geração de sólitons ópticos.

Key words: doped optical fibre, short optical pulses, cross-phase modulations, soliton.

Abstract: A experimental study on short pulse generation from praseodymium-doped fluoride mode-locked fibre lasers and gain-switched DFB semiconductor laser is presented[1]. The fiber lasers were modelocked either by using a phase modulator (PM) or cross phase modulation (XPM). In the first case, pulses of 33 ps and 75 mW (peak power) at 419 MHz were obtained. In the second case, we used a 1.55 μm gain-switched diode laser to modulate the phase of the 1.3 μm laser field via intracavity XPM. This produced 50 ps, 13 mW pulses at 2.8 GHz. In this second laser we also observed stable dark pulses with 140 to 220 ps duration, making this laser attractive as a dark soliton generator. In the case of the gain-switched (GS) diode laser, we obtained (after spectral filtering) 5 ps, 20 mW at 1 GHz. Using this GS laser we propagated solitons in 50 km of standard fibre, thus demonstrating its potentials as a simple and inexpensive soliton quality laser source.

1. INTRODUCTION

To provide future multimedia services, ultra high speed photonic networks will need to convey information at rates of the order of 100 Gbit/s. For such a system, optical pulse duration of ~5 ps or less would be desirable, which motivated increasing attention to short pulse generation techniques. Until recently, this work has been confined to the third telecommunications window based on erbium-doped fibre technology. However, following the recent advent of praseodymium (Pr^{3+})-doped fluoride fibre amplifiers, new opportunities are now possible within the second window, where the currently installed fibre base has its dispersion minimum.

In this article, we present three optical pulse sources. First, we present an actively mode-locked Pr^{3+}-doped fibre laser which could provide the basis for an ultrafast source or a clock for a high speed network based at 1.3 μm. In this experiment, pulse duration of ~ 30 ps have been generated at a repetition rate of 419 MHz with an average output power of 1 mW. The observed pulse characteristics are consistent with measurements of the fibre nonlinearity and dispersion. We present measured and calculated results for the dispersion, nonlinearity and birefringence of such a fluoride fibre, and evaluate their influence on a mode-locked fibre laser behavior. This experiment was supported by theoretical analysis including computer simulations. We wrote a nonlinear Schrödinger equation program, based on the well known 'split-step' method, to describe a pulse envelope propagation throughout a dispersive optical fibre in a nonlinear regime. A phase modulator was incorporated in the program to establish a qualitative interpretation of the phase mode-locked pulse propagation inside the laser cavity. Further, by using an optically mode-locked Pr^{3+}-doped fibre laser, we demonstrate a novel operating regime which exploits the short modulation window, achievable via optical mode-locking in the generation of either bright or dark optical pulses. The observed behavior is consistent with the stable operating regimes of FM modelocking, which are strongly influenced by the sign and magnitude of the cavity dispersion. Without dispersion control the fibre laser exhibits a 'large' normal (nonsoliton supporting) dispersion owing to contributions from both the Pr^{3+}-doped fibre and the optical modulator fibre. However, a simple method of cavity dispersion control is afforded by using a photoinduced chirped fibre grating as a laser output coupler.

Finally, we report generation and amplification of ~5 ps duration pulses from a gain-switched 1.32 μm DFB laser using a praseodymium doped fibre amplifier, PDFFA, and their subsequent soliton transmission over 50 km of standard telecommunication fibre.

2. FIBRE CHARACTERIZATION

In order to better understand the fibre lasers behavior, the fluoride fibre birefringence, dispersion and self-phase modulation (SPM) characterizations were made. We measured a normalized birefringence of $\sim 3 \times 10^{-4}$ at 1.3 μm for the fluoride Pr^{3+}-doped fibre, a value mainly due to the fibre core elliptical shape, with the same order of magnitude presented by polarization maintaining fibres and that would influence on the laser bandwidth limitation. In the case of the first laser, using a bulk phase modulator, its faces were at the Brewster's angle, which caused less transmission loss for one polarization axis than for the other. Such an optical polarization sensitive device, acting together with the highly birefringence active medium, operated as an optical filter imposing a bandwidth limitation to the laser. In fact, this high degree of birefringence introduced strong effects in all experiments employing the fluoride Pr^{3+}-doped fibre and by adjusting the mechanical control discs we could reduce these effects.

The small core of the active medium, designed to achieve high pump light intensities and thereby ensure efficient amplification, led to a considerable dispersion. The dispersion characteristics were dominated by a large contribution from the waveguide component, leading to a high normal dispersion, calculated as being ~-190 ps/nm.km at 1.3 μm, with a material contribution of ~-15 ps/nm.km and a waveguide dispersion of -175 ps/nm.km. Figure 1 shows the calculated dispersion properties of the fibre (ignoring contributions from the Pr^{3+} ion). Those values were consistent with the measured dispersion inferred from the behavior of the laser spectrum as a function of the laser cavity length. As the cavity laser length was adjusted, we observed a change in the output wavelength. The primary cause of this effect is the requirement of the optical pulse to maintain synchronization with the modulator. To compensate for the length change, the laser is forced to oscillate at a wavelength such that the group delay exactly matches at a multiple of the modulator period. The magnitude of this effect depends on the cavity dispersion. With an 11.5 m long fibre laser cavity, we measured a wavelength shift of 1.75 nm per mm of single-pass length change. From this, we infer a dispersion of approximately -1.9 ps/nm over the 11.5 m fibre length, implying a dispersion of ~-170 ps/nm.km, which is in good agreement with our estimate.

To evaluate the effect of SPM, we experimentally determined the nonlinear refractive index of our Pr^{3+} fibre, n_2, by using a Nd:YAG laser. Figure 2 shows a power dependent spectral broadening due to SPM of the Nd:YAG pulses in a 12.7 m length of the fluoride fibre. From the data (slope ~0.0088 nm/W) and taking an effective length of 8.2 m, and an effective area of 2.7 μm^2, we estimate n_2 to be ~2.0×10^{-20} m^2/W, which is close to the value for silica fibres (3.2×10^{-20} m^2/W).

Our observations demonstrated the need of understanding the intracavity parameters interaction mechanisms, in order to better control them. The best results seemed to be provided by acting over the dispersion, which motivated a theoretical investigation to account for this goal.

3. PULSE GENERATION TECHNIQUES

3.1 Electro-Optical Mode-Locking

The experimental configuration is shown in Figure 3[2]. Optical excitation was provided by a mode-locking Nd:YAG laser operating in the long wavelength wing of the Pr^{3+} ion absorption (0.32 dB/m absorption @ 1.064 μm). Since the upper state life-time of the Pr^{3+} ions is long (~110 μs) compared to the pumping period (~10 ns), the excitation appears essentially continuous. A wavelength division multiplexer (WDM) followed by ~ 1 m of high NA silica fibre was used to efficiently couple the pump into the ~ 9 m length of Pr^{3+}-doped fibre (dopant level ~ 1000 ppm, Δn ~ 0.05, average core radius, a ~ 0.7 μm). The high NA silica fibre (Δn ~ 0.04) avoids the potentially large loss arising from the mode mismatch between the

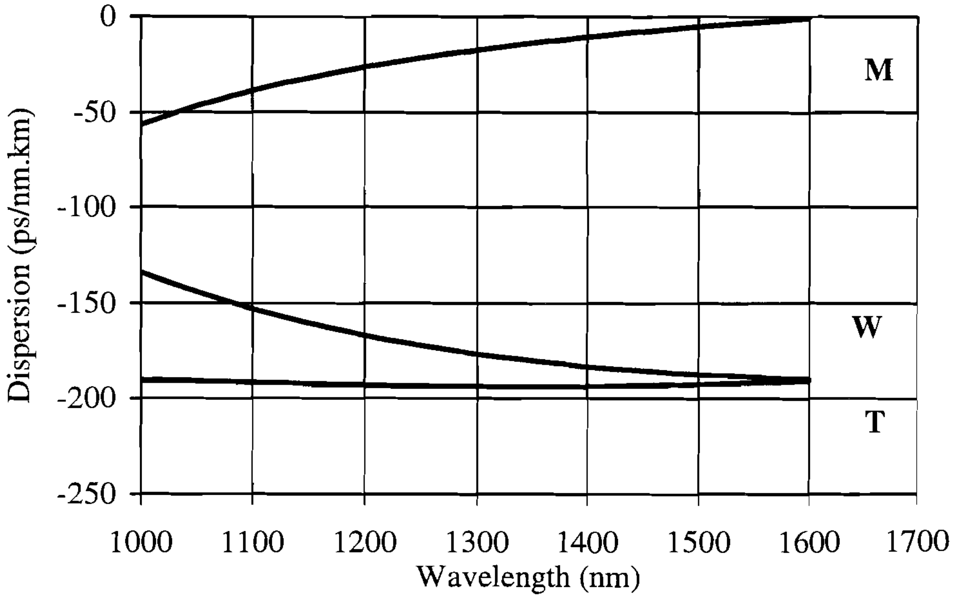


Figure 1 - Dispersion calculations for fluoride host fibre with "a"~0.7 μm and Δn ~0.05

high Δn (~0.05) fluoride fibre and the standard silica multiplexer fibre. The total loss of two splices was typically less than 1 dB. Light exiting the Pr^{3+} fibre was collimated and directed to a 0.25 mm thick glass tuning etalon, and to a mode-locker mounted close to a ~100 % reflecting mirror, M1. Adjustment of the cavity length was accomplished by mounting M1 on a translation stage. The laser cavity was completed with ~92 % reflecting output coupler, M2, butted to the leg of the WDM. In addition, a set of mechanical polarization control discs (PC) permitted adjustment of the polarization within the laser cavity. FM mode-locking was achieved using a bulk lithium niobate electro-optic phase modulator (peak phase shift of a few tenths of a radian), the frequency of which (~420 MHz) was tuned to a harmonic of the cavity mode spacing (~10 MHz). The output of the laser was monitored using a fast diode/sampling oscilloscope (temporal resolution ~29 ps) and an optical spectrum analyzer (OSA) with a resolution of 0.1 nm.

The generated pulse train behavior is illustrated in Figure 4 where two situations occurred as the interplay between narrow-stable and broad-unstable pulses. By adjusting cavity parameters such as length, polarization and etalon filtering, the unstable pulses can be eliminated. The laser output is then in the form of stable pulses with peak power of ~75 mW, duration of ~33 ps and FWHM optical bandwidth of ~0.14 nm, corresponding to the time-bandwidth product of ~0.66.

3.1.1 Theoretical Approach

To describe a pulse propagation through a dispersive nonlinear optical fibre, the nonlinear Schrödinger equation is adequate. A program that evaluates an optical pulse evolution into a fibre is capable of giving a qualitative support for various phenomena, such as the pulse shape mechanisms in a fibre laser mode-locking process. Our approach assumed a pulse propagation through a fibre where a phase modulator was incorporated. Based on the 'Fourier split-step' method, our program is appropriate to both, time and frequency, domains either in the anomalous or in the normal dispersion regime. For the aim of comparing the results to a fibre laser case, we assumed that the hypothetical cavity losses were compensated by the active medium gain. This assumption is reasonable, since in the steady state operation the saturated gain equals the cavity loss. Further we assumed that the active medium linewidth did not limit the pulse spectrum, which is a good approximation in view of the large bandwidth of Pr^{3+} emission as compared to the pulse spectrum.

For normalization of the nonlinear Schrödinger differential equation, the propagation distances were normalized to the fibre dispersion length, L_D, which is proportional to the square of the FWHM pulse width and inversely proportional to the group velocity dispersion parameter [3] The input pulse was described by a Gaussian function with no initial linear chirp. To simulate the effect of the phase modulation, a sinusoidal varying phase perturbation, δ(t), was introduced in the program. For each round trip, the transmission through the modulator was described by multiplying the pulse amplitude in the time domain by the factor $e^{j\delta(t)}=e^{j2\delta_m t}$, where δ_m is the modulation index, corresponding to the peak phase retardation for a single pass through the crystal modulator.

We considered the ideal FM mode-locking case, where a linear frequency chirp term causes the mode-locking. As can be noticed from [4] there are two groups of pulses, one is narrow and stable and the other, broad and unstable. It can also be inferred that the period of each group corresponds to one RF cycle period applied to the

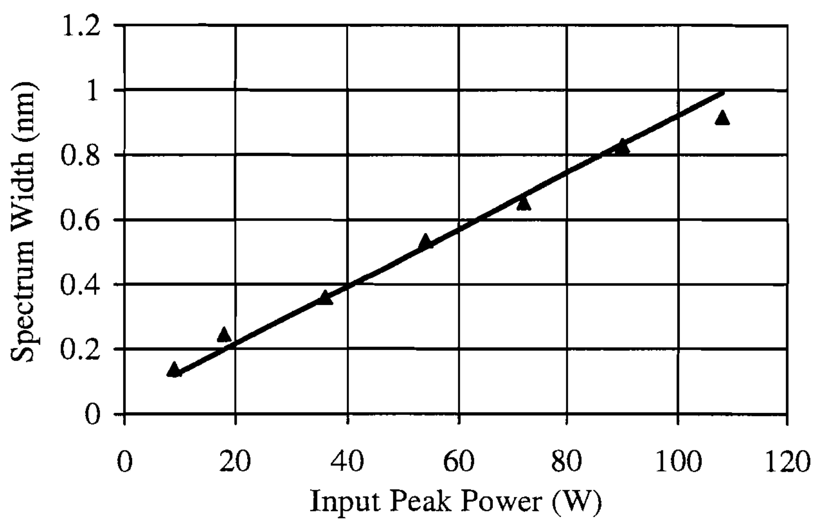


Figure 2 - SPM measurements for the Pr^{3+}-doped fluoride fibre

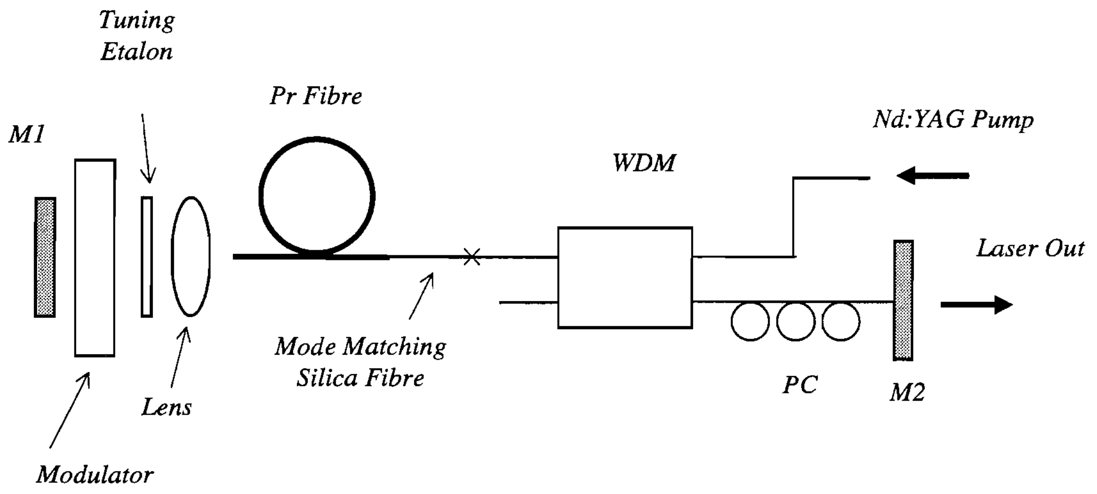


Figure 3 - 1.3 μm electro-optically mode-locked fibre laser configuration.

modulator (~420 MHz) and that for a FM mode-locking, part of the laser modes are synchronous in phase due to these RF peaks. Such generated pulses, when propagating along the cavity, suffer a temporal broadening due to the frequency chirp induced by the fibre dispersion. When propagating along the modulator, they also suffer another chirp, positive or negative, depending on which RF semi-cycle (positive or negative, respectively) is being applied. The main purpose of the simulation was to determine this equivalence, i.e. which pulse group corresponds to the positive or negative peak, for a given dispersion regime.

Basically, by assuming a normal dispersion regime (the fluoride fibre condition) and varying the sign of the modulation index, we could verify which semi-cycle caused the broadening. Our numerical simulations confirmed the presence of two operational regimes as a result of variations in the sign of the modulation index. When the pulses propagated in the fibre *normal* dispersion regime, a *positive* modulation index provided the condition to get the broad pulse group. Figure 5 presents the corresponding time-bandwidth products for the pulse, $\Delta\nu\Delta\tau$, as a function of the phase modulation sign and magnitude, after $z = 5.0\ L_D$ of propagation, corresponding to ~12500 round trips. The dispersion length, L_D, for the cavity fibre was found to be ~2.3 km at 1.3 μm, which means that the fibre cavity length corresponds to ~0.004 L_D.

The results of our approach are consistent with those already known from the Kuizenga-Siegman model [4], and gave a good understanding of the experimental laser behavior and of the pulse width dominant mechanisms. The cavity chromatic dispersion characteristics were strongly affected by the fluoride fibre small core and its characteristics became dominated by the large contribution from waveguide dispersion, leading to the high normal (non-soliton supporting) dispersion. This parameter, in association with the FM mode-locking method, have important consequences on the laser operation mode. According to the literature[4], there are

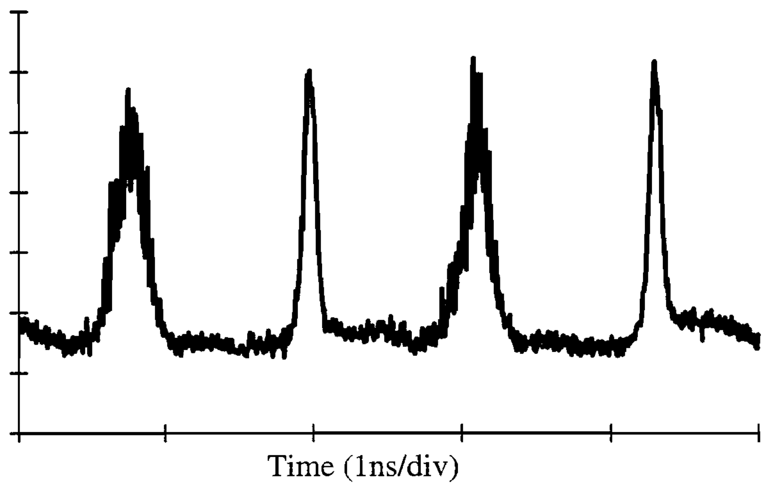


Figure 4 - Mode-locked output pulse train.

two possible solutions for the FM case, one for each extreme of the phase variation, when a pulse with a linear frequency chirp, sweeping from positive to negative values, passes through a dispersive medium. Those solutions arise from the combination, either additive or subtractive, of the two chirps on the pulse: the dispersion-induced and the modulation-induced. This means that, when an RF signal is applied to the modulator, its positive part causes a chirp with the same sign of that caused by the cavity dispersion (normal dispersion regime), which broadens and stabilizes the pulse. On the other hand, the negative RF signal part causes a chirp with opposite sign to that of the dispersion-induced.

The theoretical results confirmed the dominance of the dispersion regime on the pulse widths observed in practice, despite the non negligible importance of SPM. We suggest that the combination of SPM and large normal dispersion associated with the Pr^{3+} fibre are responsible for the increased time-bandwidth product (chirp). Such excess bandwidth has been noted in previous work[5] on passively mode-locked Pr^{3+} fibre lasers. It should be noted that by including (intra- or extra-cavity) dispersion compensating elements, shorter, transform-limited pulses should be possible, which motivated our next mode-locked fibre laser experiment, described below.

3.2 All-Optical Mode-Locking Using XPM

This laser configuration is shown in Figure 6 [6] . Optical excitation of the ~8 m-long Pr^{3+}-doped fibre was provided via an Nd:YAG laser operating at 1.064 μm and launched through a wavelength division multiplexer, WDM1. The end mirror, M1, of the linear cavity was a 100 % reflector butted to the Pr^{3+}-doped fibre. The output coupler, M2, comprised either a ~92 % reflecting mirror (butted to the output leg of WDM3), or an optically written fibre grating constructed by the 'stepped-chirp' phasemask method [7]. The 8 mm-long grating reflects ~70 % over a 2.24 nm bandwidth (centered at 1.3 μm) implying a dispersion of ± 35 ps/nm. With this grating as an output coupler, the laser threshold was measured to be ~45 mW with, ~1.9 mW of mean output power at a wavelength of 1.3 μm for ~100 mW absorbed pump power. In the absence of the grating reflector, a filter was included in the laser cavity to provide control of the output spectrum. Active mode-locking was achieved this way: a stream of optical pulses forced the laser mode-locking through the nonlinear effect of cross phase modulation, XPM. The 35 ps duration driving pulses from a gain-switched DFB laser (at 1.564 μm) were amplified (in an erbium-doped fibre amplifier) to a maximum mean power of 30 mW and allowed to propagate along a 500 m length of silica fibre (between WDM2 and WDM3) within the Pr^{3+} fibre laser cavity. This fibre was chosen to have a dispersion zero at ~1.44 μm such that the group delays at 1.3 μm and 1.564 μm were reasonably matched. The total (normal) dispersion of the uncontrolled laser cavity was estimated to be - 14 ps/nm, resulting from - 4 ps/nm and - 10 ps/nm contributions from the Pr^{3+} fibre and modulator fibre, respectively. Therefore, by including the fibre grating, the laser cavity could be made to have a net soliton supporting dispersion of + 21 ps/nm. A set of mechanical polarization controllers (PCs) were also included in the cavity.

In a conventional FM mode-locked laser (driven by a sinusoidal phase profile), two possible solutions exist, one for each extreme of the phase modulation, where the so-called 'positive mode' of operation corresponds to the maximum phase variation. Because the two modes have opposite signs of frequency sweeps (chirps), a fixed sign of dispersion acts to compress and stabilize one of the modes and to broaden and destabilize the other. This was

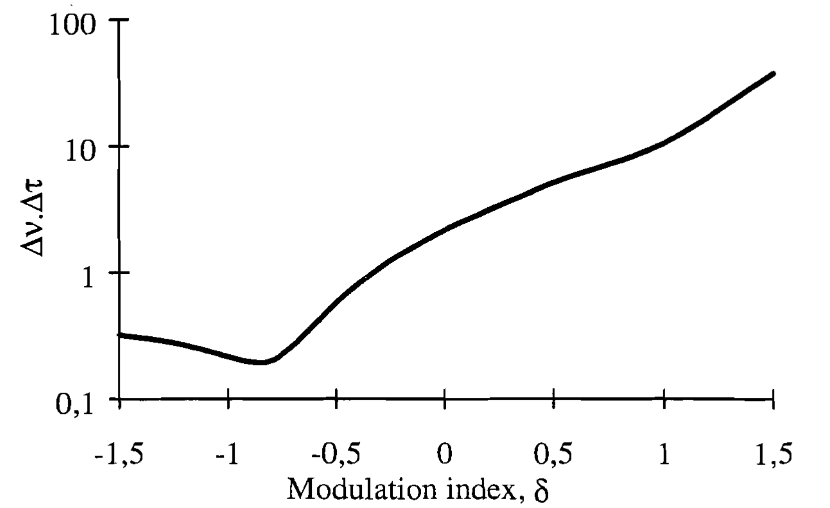


Figure 5 - Time-bandwidth product as a function of the normalized phase modulation index in the normal dispersion regime.

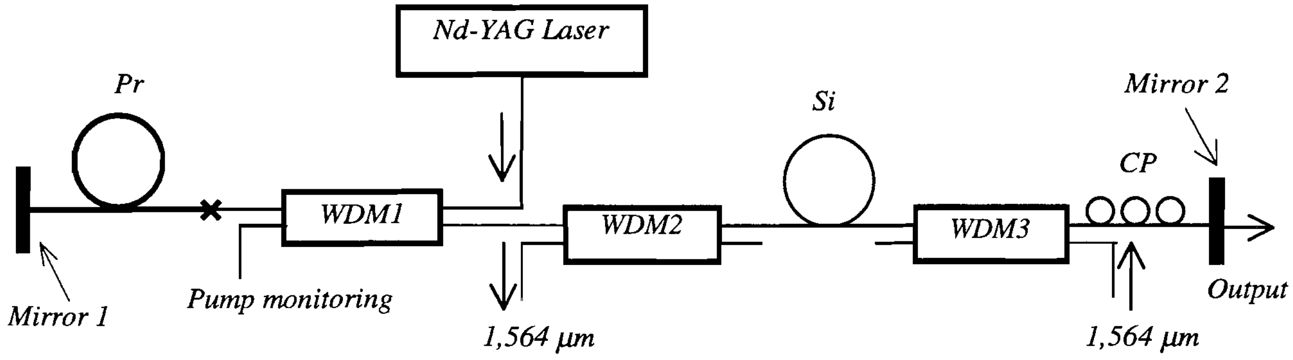


Figure 6 - *Optically mode-locked praseodymium fibre laser.*

observed in the electro-optical phase mode-locking described later: for the normally dispersive Pr^{3+} fibre laser cavity, the positive mode is destabilized. For the optically FM mode-locked laser described here, the typical modulating profile consists of a periodic train of short positive phase 'windows' separated by (broad) unmodulated regions.

Figure 7(a) shows the output of the optically mode-locked laser (without fibre grating) operating at a repetition frequency of ~ 700 MHz, displayed on a fast photodiode and sampling oscilloscope. The short positive phase window defined by the XPM process resulted in a clearly visible negative impulse response of the (AC coupled) photodiode. The combination of the imposed frequency shifts from the XPM and the normal dispersion tends to 'push' light out of the modulated time slot into the unmodulated region, giving rise to a broad, essentially CW output, separated by optical 'holes' or dark optical pulses. To ascertain the depth of the dark pulses, the laser output was observed using a streak camera. A typical result is shown in Figure 7(b), and illustrates a dark pulse (at a wavelength of 1.31 μm) with a width of ~ 160 ps and a modulation depth approaching 100 %. The critical role of walk-off in determining the dark pulse duration was noted: tuning the laser wavelength from 1.29 to 1.315 μm allowed the pulse widths to be adjusted from 220 to 140 ps, respectively (a modulation depth in excess of 95 % was maintained during these measurements).

The results presented in Figure 8(a) and (b) allow a direct comparison of the output of the 1.3 μm XPM mode-locked laser before and after inclusion of the chirped fibre grating at the highest repetition rate achievable (~ 2.8 GHz). Without the grating, the results are depicted in Figure8(a). However, by introducing the grating to the cavity, and thereby ensuring a net positive dispersion, the mode could be stabilized. This is clearly visible from Figure 8(b), where we observe a stream of narrow, ~ 50 ps, bright optical pulses corresponding to the positive phase window.

3.3 DFB Laser Gain-Switching

When the gain of a semiconductor laser is switched by an electrical pulse from a state below threshold into inversion, the laser generally emits several relaxation oscillations. The attractiveness of this technique is its

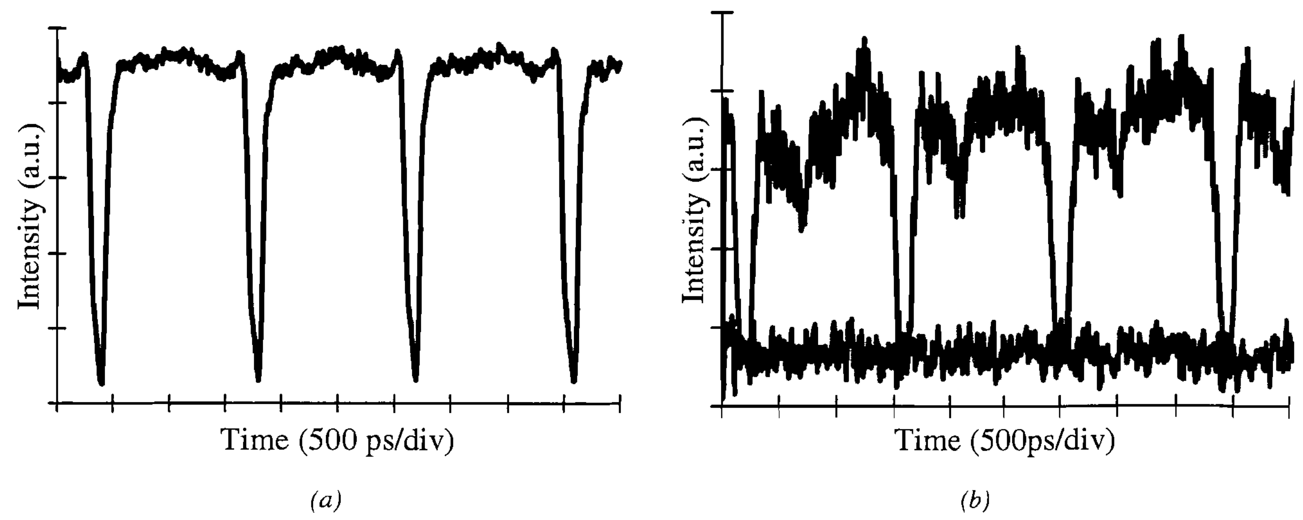


Figure 7 - Dark laser output at 700 MHz displayed on (a) photodiode/sampling oscilloscope, ar (b) streak camera.

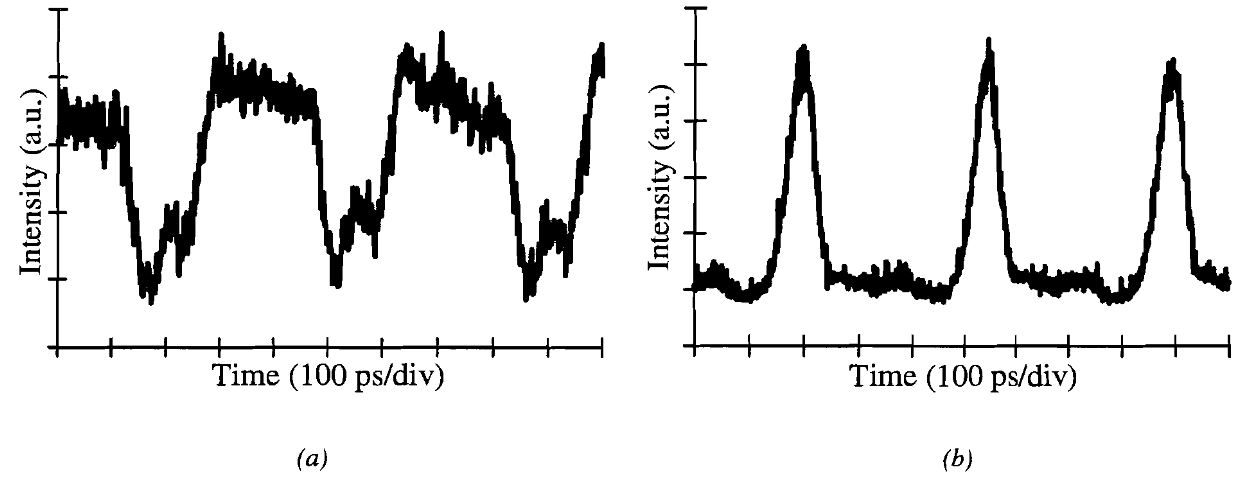


Figure 8 - (a) Dark and (b) bright pulses at 2.8 GHz, displayed on a photodiode/sampling oscilloscope combination.

simplicity. The standard gain switching arrangement is to drive a laser, biased below threshold, with an electrical RF generator. The idea is to catch the first spike of relaxation oscillation without exciting subsequent ones.

Figure 9 shows a typical evolution in the electron and photon densities during a gain switch cycle. At $t = 0$ a current pulse is applied to a laser which is biased way below threshold. The initial rate of increase in photon density is very low due to its low initial value. Without being significantly consumed by stimulated emission, injected electrons rapidly build the carrier density up to a level above the conventional lasing [8].

A higher peak inversion level will lead to a shorter pulse width. A slower buildup of lasing photons will allow the

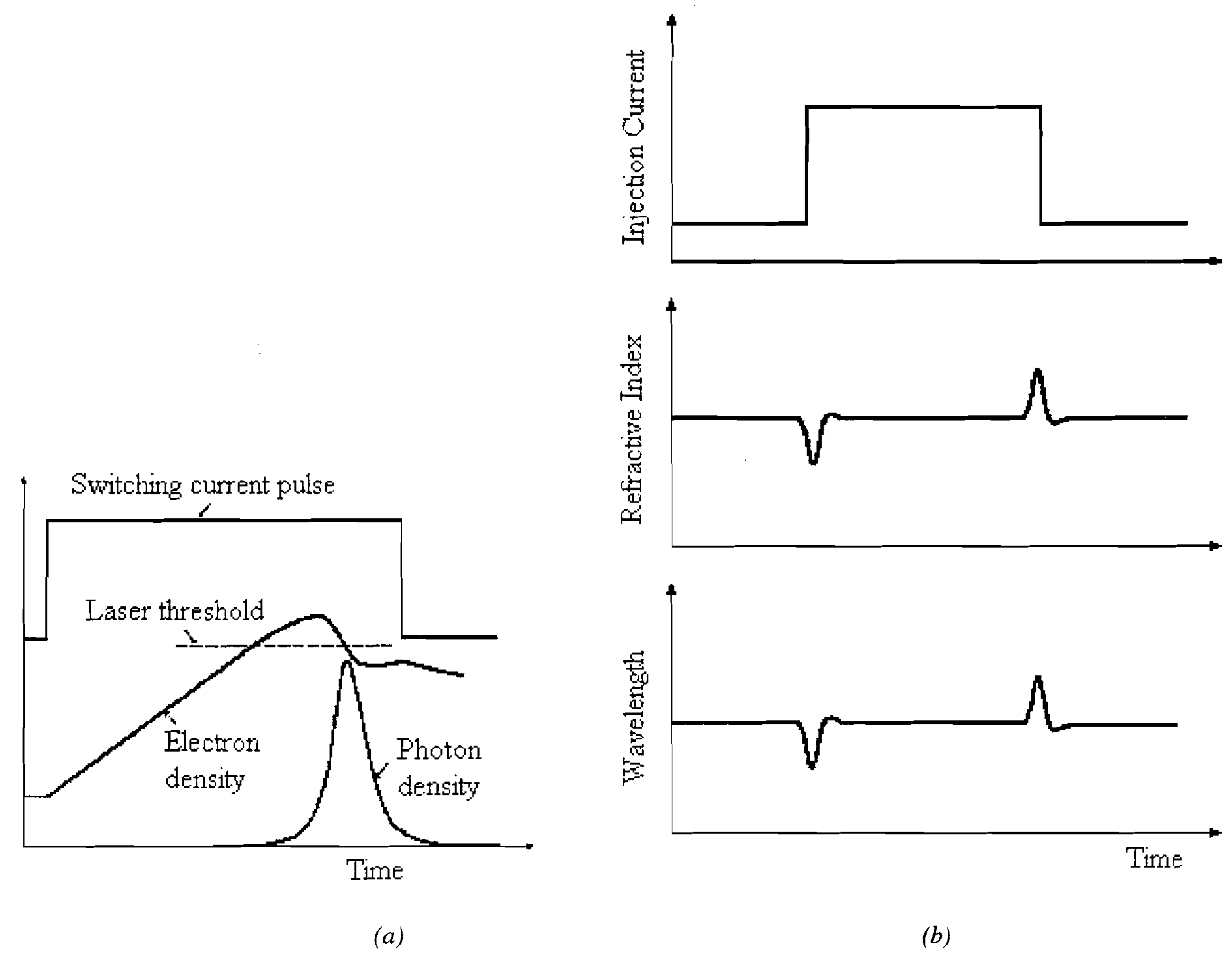


Figure 9 - (a) Typical evolution of the photon and electron density during a gain switch cycle, and (b) spectral broadening process in the output of a modulated laser. Note: in (b) the time scale is bigger than in (a).

carriers a longer time to build up to a higher inversion level. This type of gain switching assumes a large pump current pulse which contains an amount of charge many times larger than that for threshold inversion. Under this situation, a large initial inversion will be achieved by having a long delay in the onset of stimulated emission, which will happen if the laser is unbiased. However, if the drive pulse contains a relatively small amount of charge, it has been observed that the shortest optical pulse is obtained when the laser is biased slightly below threshold. If biased above threshold, a large amount of pre-existing stimulated emission will clamp the maximum inversion at a level not much higher than the threshold level; on the other hand, the limited amount of charge delivered by the current pulse may not be able to make a substantial positive inversion, thus leaving the optimum bias point to be slightly below threshold.

The experimental arrangement used was that shown in Figure 10[9]. The pulse source was a DFB laser operating at ~ 1.323 μm, with a CW lasing threshold of 16 mA, frequency bandwidth between 0.1 and 5 GHz, optical CW power greater than 4 mW and spectral CW linewidth less than 10 MHz. The RF generator produced an electrical signal of nearly 1 GHz and maximum power of + 5 dBm to the RF amplifier, that operated in the range of 700-4200 MHz with maximum output power of + 28 dBm. A tunable optical filter was placed at the laser output for spectral improvements. For chirping compensation a piece of standard dispersion shifted fibre was employed. The pulse monitoring system consisted of a Pr^{3+}-doped fluoride fibre amplifier, PDFFA followed by an spectral analyzer and an autocorrelator, optimized for the second window. The fibre amplifier was necessary due to the low sensitivity of the autocorrelator. A set of mechanical polarization control disks, PC, was included to match the polarization state of the incident light to one of the axes of the birefringent fibre amplifier.

From the time-spectral linewidths of the output pulses, it was estimated that it was necessary about 8.5 ps/nm for compensating the frequency chirp, due to the gain-switching. From the standard dispersion shifted fibre, DSF, characteristics, with - 17 ps/nm.km @ 1.323 μm, it was estimated that ~500 m would fulfill the requirements. The DSF length was further adjusted during the experiment to the laser polarization and modulation laser conditions and to the filter bandwidth. This way, the initial 500 of fibre were cut until the point where pulse compression stopped. Initially, it was employed a ~1.5 nm bandwidth filter, operating between 1.29 and 1.325 μm. The fibre length was reduced to ~450 m at a repetition rate of ~1040 MHz. Figure 11 shows the autocorrelation of the DFB output (Δt ~14.1 ps, FWHM), the filter output (Δt ~14.1 ps) and the DSF output (Δt ~4.7 ps). At the laser output, the pulse has pedestal due to the gain-switching chirp, which was slightly reduced by the filter.

Figure 12 shows the correspondent spectrum at the DFB, tunable filter and DSF outputs. Note that they present nearly the same shape and width. It is probably due to the fact that both, the DFB pulse linewidth and the filter bandwidth, have almost the same value. Furthermore, the pulse peak power and the fibre length did not allow a significant self-phase modulation.

The time-bandwidth product, ideally equal to 0.334 and 0.461 for *sech*^{2} and *gaussian* profiles, respectively, was reduced by a factor of three after the pulse propagation

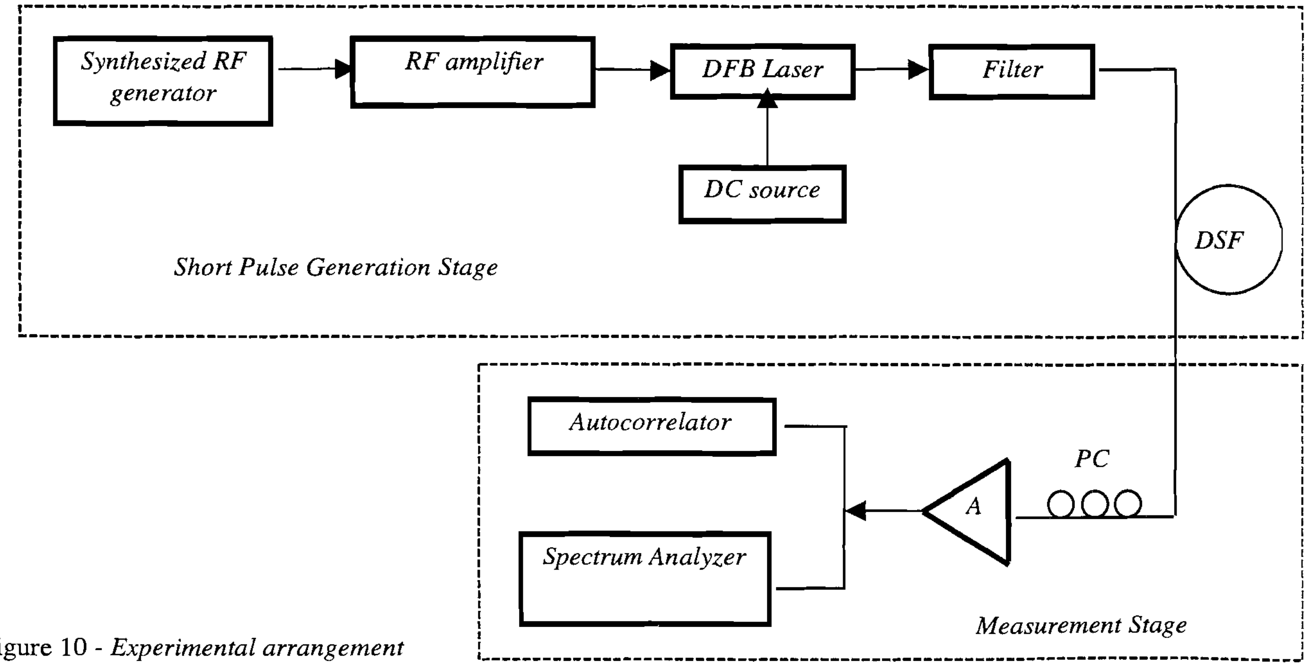


Figure 10 - *Experimental arrangement*

through the DSF. At that point, with the product being nearly equal to 0.9, a considerable chirp still remained. In fact, a linear medium, such as the dispersion shifted fibre, is not capable of totally eliminate the chirp, which is nonlinear. To reduce this chirp, the filter was replaced by a narrower one, with ~0.4 nm. The new pulses train was generated at a repetition rate of 1000 MHz and the DSF length was reduced to ~ 360 m. Figure 13(a) presents the pulses at the laser ($\Delta t \sim 15.4$ ps *RMS*[10]), the filter ($\Delta t \sim 8.6$ ps) and the DSF ($\Delta t \sim 7.5$ ps) outputs. In these cases, the time widths were greater than in the later since the pulse pedestal was considered. The pulse at the laser output was two times wider than the one after compression by the DSF, besides having a much bigger pedestal. After some polarization and laser modulation adjustments, the pulse width was reduced. Furthermore, the narrower filter allowed a greater chirp reduction, which also decreases the pulse pedestal, as well as the DSF compression. From Figure 13(b) it can be noticed that the filter reduced the red components of the output laser spectrum. At the DFB output, the RMS time-bandwidth product was ~0.99, decreased to ~0.50 after the filter and to ~0.43 after the DSF. Due to the pedestal and to the spectrum asymmetry, those values were calculated by the RMS method.

4. SOLITON TRANSMISSION

An important manifestation of the fibre nonlinearity occurs in the anomalous dispersion regime where the fibre

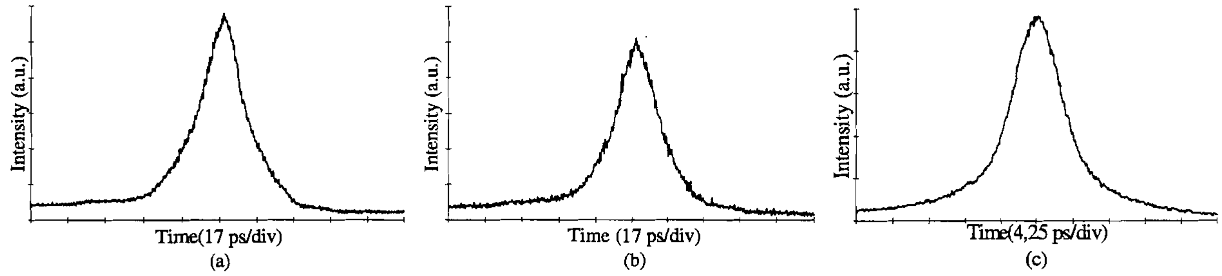
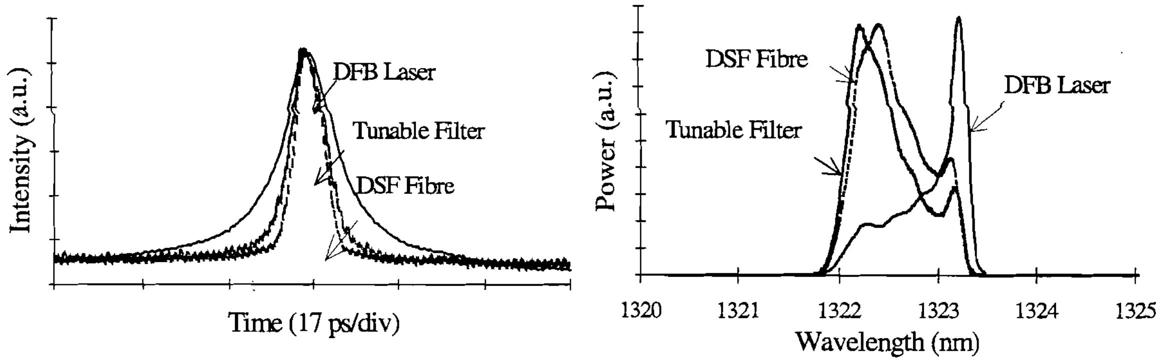


Figure 11 - Autocorrelation of the pulses after the: (a) DFB laser, (b) tunable filter and (c) DSF.



(a) *(b)*

Figure 12 -Pulse (a) autocorrelation and (b) spectrum at the DFB laser, filter and DSF outputs.

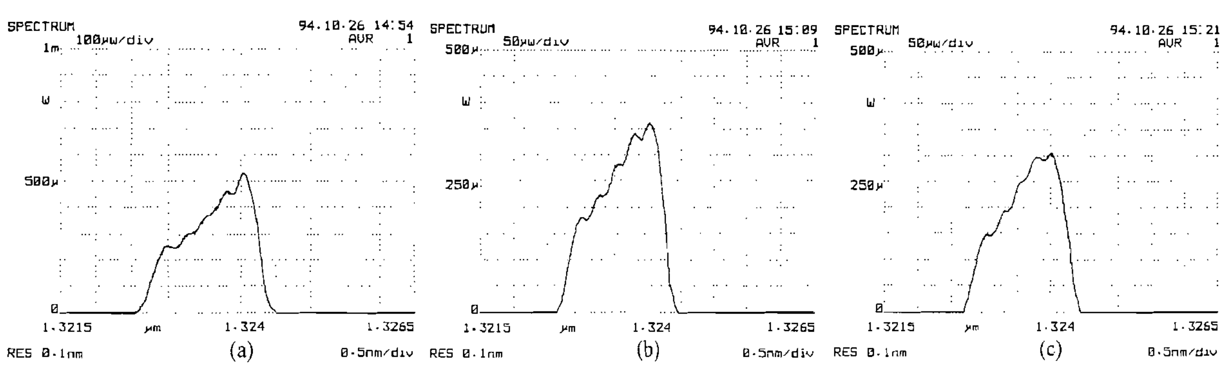


Figure 13 - Spectrum of the pulses after the (a) DFB laser, (b) tunable filter and (c) DSF.

can support optical solitons through an interplay between the dispersive and nonlinear effects. The term soliton refers to special kinds of waves that can propagate undistorted over long distances and remain unaffected after collision with each other. In the context of optical fibres, the motivation behind soliton-based communication systems is their potential of providing data transmission over long distances (>1000 km) at bit rates approaching 100 Gbit/s if the fibre loss is compensated by using a suitable soliton-amplification scheme.

In an ideal soliton-based communication system input pulses launched into the fibre should be unchirped, have a hyperbolic secant shape, and have a peak power determined from the well known nonlinear Schrödinger equation to obtain a fundamental soliton (order N=1). In practice, pulses would deviate from the ideal requirements necessary to launch the fundamental soliton, and one must determine the corresponding tolerance levels. The effect of an initial frequency chirp on soliton formation can be detrimental simply because it superimposes on the SPM-induced chirp and disturbs the exact balance between the group velocity dispersion, GVD, and SPM effects necessary for solitons. The effect on initial frequency chirp can be evaluated numerically from the input pulse amplitude expression

$$u(0,\tau)=N\,sech(\tau)exp(-iC\tau^2/2),$$

where C is the chirp parameter, τ is the pulse duration and N is the soliton order. The quadratic form of phase variation corresponds to a linear chirp such that the optical frequency increases with time (up-chirp) for positive values of C. The formation of a soliton is expected for small values of $|C|$ since solitons are generally stable under weak perturbations. The critical value depends on N and is found to be $C_{cr} \sim 1.64$ for $N = 1$ [5]. It also depends on the form of the phase factor in the above equation. From the system standpoint the initial chirp should be minimized as much as possible. This is necessary because even if the chirp is not detrimental for $|C| < C_{cr}$, a part of the pulse energy is shed as a dispersive tail during the process of soliton formation.

In this experiment[11], we demonstrate the use of praseodymium doped fluoride fibre amplifiers (PDFFAs) to transmit solitons in the second window, over practical lengths of standard telecommunications fibre at gigahertz repetition rates, using a simple semiconductor laser source [1].

The experimental arrangement was that shown in Figure 14, and is similar to that described in the previous section. The pulse source was a 1.32 μm DFB laser, which was gain-switched at a frequency of 1 GHz. The output from the DFB laser was passed through a filter and a length of normally dispersive fibre, thereby generation low-chirp pulses with duration as short as 5 ps. A PDFFA was used to amplify the laser output giving an average power of 2.6 mW. As before, a set of polarization control disks was placed before the PDFFA.

Figure 15 shows the autocorrelation of the resulting pulses, which indicates a pulse duration of 5.1 ps FWHM, assuming a Gaussian intensity profile. As it is well known, a soliton forms in an optical fibre owing to the combined effects of self-phase modulation and anomalous group velocity dispersion. When the peak power of the pulse equals the soliton power an $N = 1$, soliton forms, which propagates without changing its shape, and, in particular, maintains its duration. In this experiment the signal wavelength was chosen to be slightly longer than the dispersion zero, so that we are operating in the anomalously dispersive regime, where a soliton can form. However, the 18 dB loss of this length of fibre means that peak power cannot equal the soliton power along the full 50 km length of fibre. Nevertheless, for an appropriate launched power, it is still possible to transmit the pulse with little distortion, as demonstrated in Figure 15, which shows the autocorrelation of the pulses after transmission

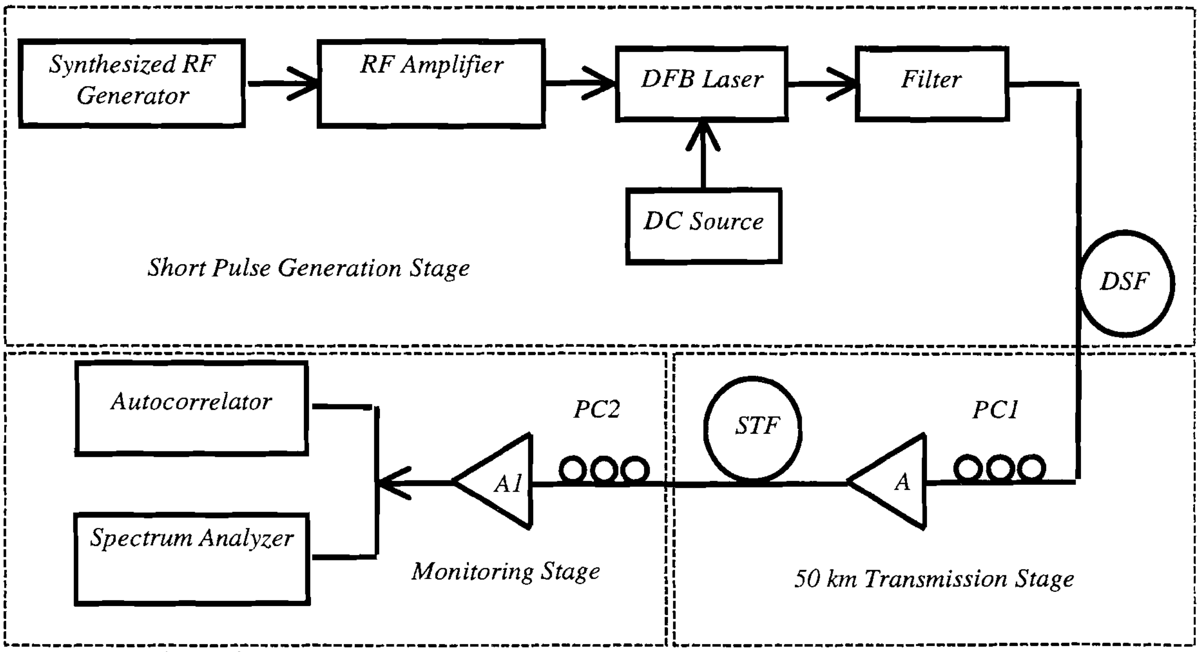


Figure 14 – Experimental arrangement

through 50 km of standard fibre. The transmitted pulses have compresses very slightly to 4.9 ps (assuming a Gaussian intensity profile), which we believe is caused by the aforementioned inability to form an N = 1 soliton along the full length of fibre (higher order solitons were excited). This also accounts for the small pedestal evident in the autocorrelation of the transmitted pulses. Other possible explanations for the pedestal are frequency chirp of the input pulses, deviations from the ideal $sech^2$ pulse shape associated with a soliton and the cumulative effect of slight misalignment of the polarization from the axes of several (birefringent) PDFFAs in series..

The low dispersion of the standard fibre allowed soliton generation at low power levels. For the repetition rate of 1 GHz, the ~2.4 mW average power at the fibre input, corresponding to 324.3 mW peak power, allowed sixth order soliton excitation. The output spectrum, Figure 16, presented side bands, probably due to high order soliton effects. Note that, due to the attenuation, lower order solitons were excited along the transmission. The time-bandwidth products for the input and output pulses from the standard fibre were found to be 0.23 and 0.29, respectively. Ideally, those values should be equal to 0.26, which indicates that the initial chirp due to the gain-switching method did not affected significantly the soliton transmission and that the chirp compensation through the dispersion shifted fibre and the spectral filtering was able to maintain the chirp value below its critical value, C_{cr}. Furthermore, from the input pulses, it was estimated a soliton period of about 76.6 km, meaning that the fibre length corresponded to 65 % of a soliton period.

5. CONCLUSIONS

This article presented a study of short pulse generation, amplification and propagation in the second optical communication window. It described the dispersion, nonlinearity and birefringence characterization of a Pr^{3+}-doped fluoride fibre and two kind of sources: a mode-locked praseodymium-doped fluoride fibre laser, in two configurations, and a gain-switched DFB semiconductor laser. In the first case, an FM mode-locked fibre laser, the large contribution from the active medium high normal (non soliton supporting) waveguide dispersion dominated the cavity dispersion. The combination of the phase modulation (chirp) semi-cycles peak signs and magnitudes, and the cavity dispersion sign and magnitude, proved that they must lead to, at least, a mutual compensation between them in order to narrow and stabilize the pulses. The two possible solutions for an FM mode-locking case were observed, one for each peak of phase variation. A numerical approach was presented to give a qualitative support to the experimental observations. By tracking a phase modulated pulse propagation through a fibre, we demonstrated the main pulse shaping mechanism.

Through the second fibre laser configuration, we have shown that both bright and dark pulses can be generated in an optically mode-locked fibre laser. The combination of the short positive phase window provided by XPM and the large and normal dispersion associated with the Pr^{3+}-doped fluoride fibre laser cavity favors the production of dark pulses. The width of dark pulses could be controlled via the walk-off between the modulating and laser wavelengths. By controlling the walk-off more precisely and using short driving pulses, it may be possible to generate picosecond duration dark pulses. The generation of dark pulses in the manner described in this article may be useful in the further assessment and development of amplified dark soliton transmission systems.

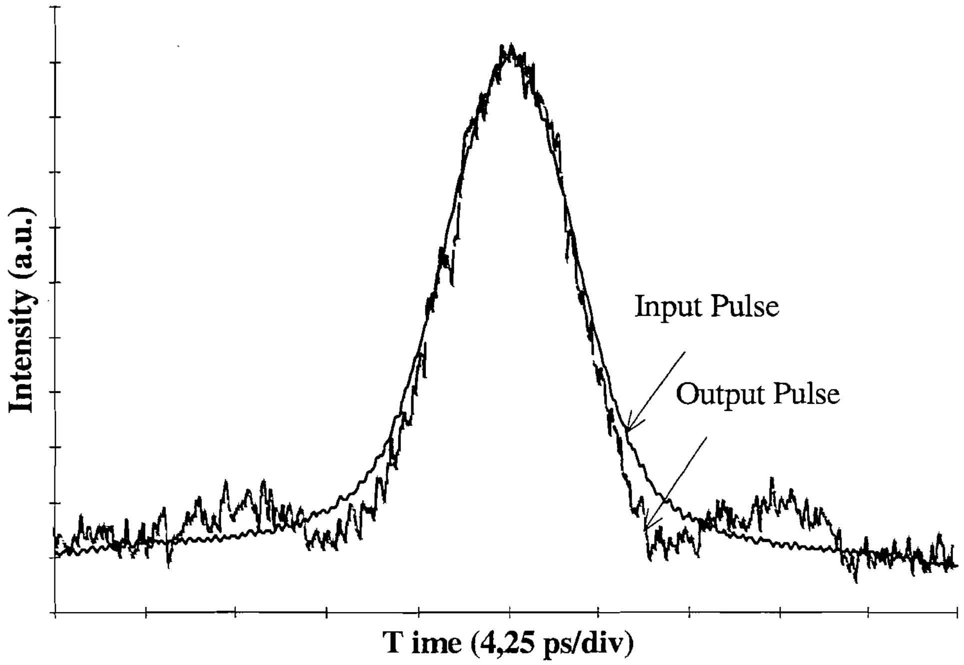


Figure 15 - *Autocorrelation of pulses before entering and exiting 50 km of standard fibre*

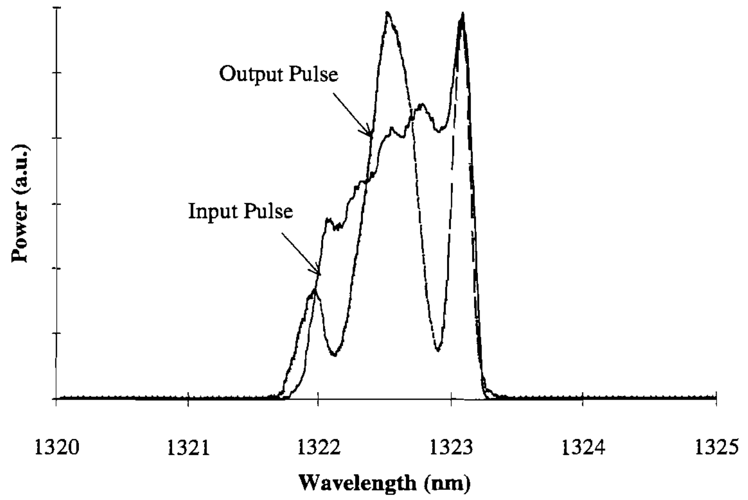


Figure 1 - Spectrum of the pulses entering and exiting the 50 km standard fibre.

Optical short pulse (~5 ps) generation was also demonstrated by gain-switching an 1.3 μm DFB laser. The linear chirp generated by this method was compensated by a standard dispersion shifted fibre and filtered by a tunable Fabry-Perot filter, which narrowed the pulse and reduced its pedestal. We have demonstrated that praseodymium doped fluoride fibre can be used to amplify the pulses from this gain-switching to solitonic power levels. This simple source of picosecond pulses may allow the reuse of currently standard telecommunication fibres in the ultra high speed photonic networks of the future. Finally, we have demonstrated the transmission of 1 GHz 5 ps duration solitons around 1.3 μm, over 50 km of standard fibre. The source was a gain-switched DFB laser, and the amplification was provided by PDFFAs.

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