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Pulse Repetition-Rates in a Passive, Self-Starting, Femtosecond Soliton Fibre Laser.

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Abstract

Several unusual pulsing modes are observed in a self-starting, passively mode-locked erbium fibre soliton laser capable of generating pulses with durations as short as 320 fsec.

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Rare-earth doped optical fibres offer wide gain bandwidths and provide an ideal medium for the generation of ultra-short optical pulses. To date research in mode-locked fibre lasers has centered on active mode-locking schemes incorporating fast phase [1] and amplitude modulators [2]. However, the large non-linear effects obtainable in optical fibres make passive mode-locking an attractive proposition. A self-starting, passive mode-locking scheme based on the reflection properties of the Non-linear Amplifying Loop Mirror (NALM) [3] has recently been reported [4,5]. The system is capable of both picosecond/nanosecond duration square pulse operation [4] and ultra-short femtosecond soliton generation [5,6]. In this paper we discuss the various modes of operation of the laser and present results on pulse repetition rates, an important characteristic for a practical source of ultra-short solitons.

The laser configuration is illustrated in figure 1. The switching characteristic of the NALM dictates that the minimum loss per cavity round-trip pulse forms are either square pulses with a peak intensity determined by the switching power of the loop, or solitons. Both of these pulse forms can propagate in a non-linear medium with a constant phase across their entire envelope and this characteristic enables complete switching by the NALM [7]. In order to self-start, noise is required at the NALM input to enable either the square or soliton pulse forms to develop. The noise is provided by reducing the linear cavity loss to a level sufficient for the onset of CW lasing. This is achieved either by applying a birefringence induced non-reciprocal phase bias within the NALM or by arranging for asymmetric splitting at the NALM coupler. This latter option would permit the system to be constructed entirely of polarisation-maintaining fibre, thus improving system stability. Both square pulses with durations in the pico/nano -second range [3] and femtosecond soliton pulses [4,5] have been observed experimentally with the system operating at 1.55 μm. The shortest pulses so far generated had a duration of 320 fsec [4,5] and a corresponding time bandwidth product of 0.32 (see figure 2).

As well as having two distinct modes of pulse generation, the system has at least three distinct regimes of operation with regard to pulse repetition rates. During square pulse operation (which constitutes the most stable operation of the system), pulses are generated at the cavity round-trip frequency. In this regime the repetition rate is stable with regard to changes in input pump power, provided that the pump power is not reduced to a level below which the pulsing cannot be sustained. The peak power of the square pulses remains clamped to the switching power of the NALM loop and, as the pump power to the system is increased, the extra power circulating in the cavity is taken up by a corresponding increase in pulse width. Square pulses generated with a 104m NALM at a variety of input pump powers are shown in figure 3 and illustrate the pulse broadening with increasing pump level.

The transition from the square pulse to the soliton regime of operation is most readily induced by changing the NALM phase bias. Three distinct modes of repetition rate behaviour have been observed. Firstly, as the NALM phase bias is slowly altered the square pulse is seen to break up into tightly-packed bunches of solitons, the bunches repeat at the cavity round-trip frequency. The situation is illustrated in figure 4. As the phase bias is adjusted close to the point at which the transition from square pulse to soliton behaviour occurs, large deviations from the expected 2:1 aspect ratio of the coherent spike to the pulse shoulder in the background free autocorrelation traces of the square pulses are observed. This observation indicates that substructure on a femtosecond timescale develops within the square pulse just prior to the transition to the soliton regime. Pulse repetition rates as high as 100 GHz (as determined from autocorrelation scans) have been observed within the pulse bunches.

Secondly the system can enter a soliton regime in which the solitons are no longer bunched, but occur seemingly randomly distributed over the entire cavity round-trip period, the pulse patterns repeating at the round-trip frequency. An example of this random pulsing is shown in figure 5a, where, since the detector response time (55 psec) is far longer than the pulse duration (500 fsec), the trace effectively displays the pulse energy. The pulse with twice the amplitude of the others is due to two pulses occuring within the detector response time and illustrates the quantisation of pulse energy associated with solitons being the preferred switching unit for system operation. Note that because of this energy quantisation, more pulses must circulate in the cavity if the pump power is increased, i.e. the average repetition rate must increase in order to obtain more output power. Moreover, no discernible change in the output soliton autocorrelation traces and spectra with input pump power have been observed with the system. This is in contrast to the square pulse mode in which the pulse peak-intensity is clamped and increased circulating energy is taken up by an increase in pulse duration.

By appropriate adjustment of input pump power and birefringence of the NALM it is possible to enter the third pulse repetition rate regime and obtain pure harmonic mode-locking as illustrated in figure 5b. However, in this mode the system is very sensitive to slight changes in pump power. Exactly what factors determine which of the three regimes of soliton generation is encountered are not yet understood. One possibility is that cross-phase modulation between counter-propagating pulse bunches within the NALM loop can play a significant role in its switching operation. The effects of cross-phase modulation would be maximised for tightly bunched pulse trains.

In conclusion, the various pulsing regimes of operation of the femtosecond soliton laser have been clarified. From a practical point of view, stabilisation of pulse repetition rates is an important goal. We have recently obtained encouraging results by incorporating within the system a pulse multiplier consisting of a recirculating fibre ring delay line. Results of these experiments will be presented at the conference.

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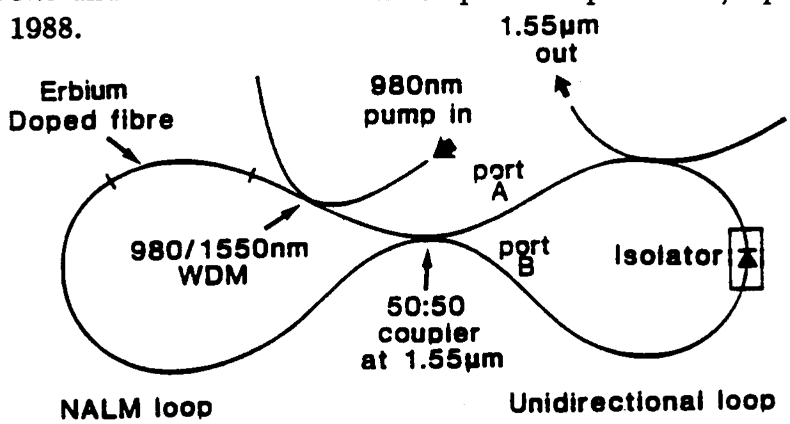

Figure 1)

Experimental configuration of the self-starting, passively mode-locked fibre laser.

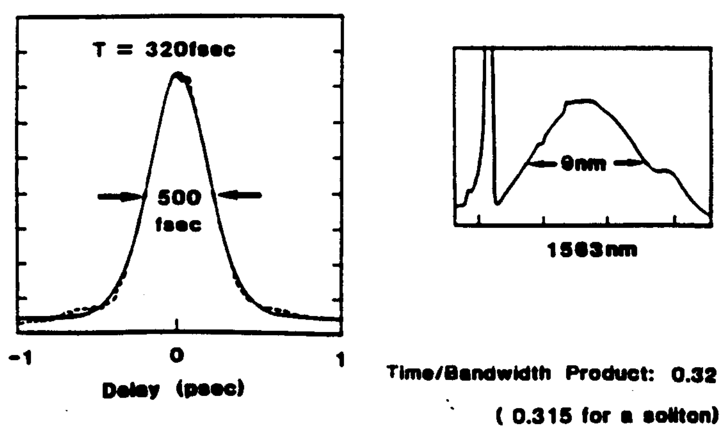

Figure 2)

Background free auto-correlation trace and optical spectra of 320 femtosecond soliton pulses. the solid line autocorrelation profile representa a non-linear least squares fit to the experimental data on the assumption of a $\mathrm{sech}^2\tau$ pulse form.

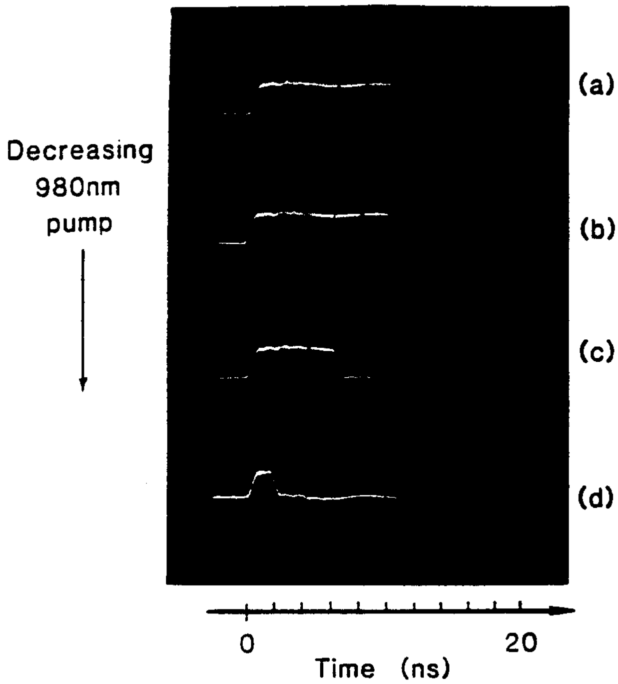

Figure 3) Output pulse shapes for 104 m mode-locked fibre laser as a function of pump power. Input 980 nm pump powers were (a)155 mW, (b)115 mW, (c)75 mW and (d)40 mW. The system self started at an input pump power of 80 mW.

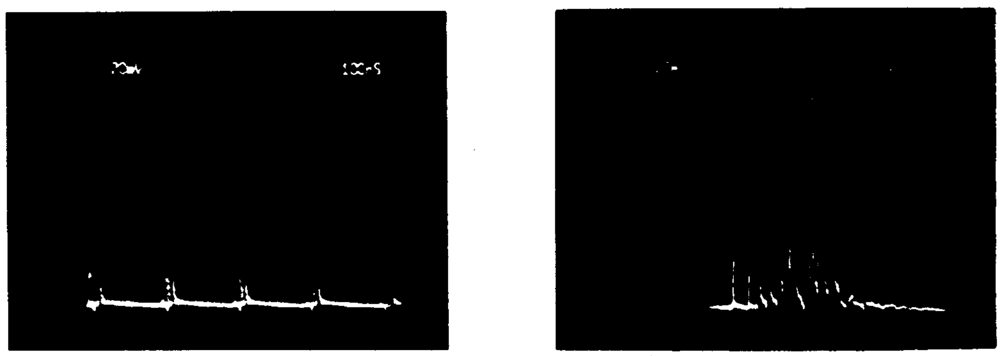

Figure 4) (a) Soliton pulse bunches circulating around the cavity at the cavity round trip frequency. (b) Exploded view of an individual soliton bunch.

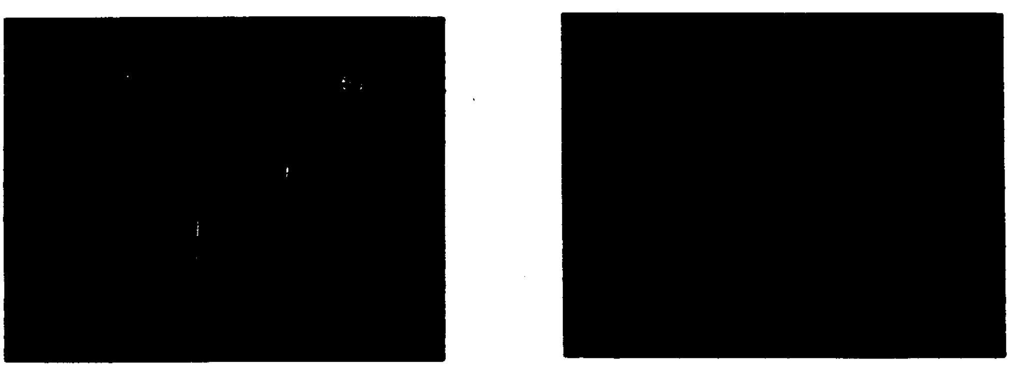

Figure 5) 450 fsec soliton pulse trains. (a) Pulses randomly spaced but well separated. The pulse of apparently twice the amplitude of the others is due simply to two pulses arriving within a time period less than the detector response time. (b) Pure passive, harmonic mode-locking (f=67.2 Mhz, the 16 th harmonic of the cavity round-trip frequency).