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Switching and passive mode-locking of fibre lasers using nonlinear loop mirrors.

D.J. Richardson, R.I. Laming and D.N. Payne

Optoelectronics Research Centre, University of Southampton, U.K.

ABSTRACT

Ultrafast all-optical, fibre optic switches are of great interest as all-optical signal processing elements in telecommunication systems and as passive mode-lockers for all-fibre mode-lock lasers. We describe the operation and characteristics of two such switches, the conventional and amplifying Sagnac switch, and describe the use of these components in a recently developed, passive, self-starting, mode-locked erbium doped fibre laser capable of the generation of solitons with durations as short as 320 femtoseconds.

1. INTRODUCTION

In recent years much work has been devoted to the development of all-optical, switches compatible with optical fibre technology. The physical mechanisms employed so far to perform all-optical switching have been based on third order nonlinear effects such as Self-Phase and Cross-Phase Modulation (SPM and CPM respectively), which have response times of the order of a few femtoseconds. It is this ultrafast response time with its potential for switching and routing in ultra-high bit rate telecommunication schemes that provides the main motivation for all-optical switching studies. The fast switching speeds are also interesting for high speed optical computers and in the generation of ultrashort pulses. In this paper we describe the operation and characteristics of two all-fibre, ultrafast switches which have recently become of considerable interest, the Nonlinear Optical Loop Mirror (NOLM) and the Nonlinear Amplifying Loop Mirror (NALM). We then describe how such switches can be used within laser cavities to act as passive mode-lockers before describing in detail the results of experiments recently performed on a passive, self-starting fibre laser capable of the generation of solitons with durations as short as 320 femtoseconds.

2. FIBRE BASED OPTICAL SWITCHES

A number of all-fibre switching schemes have been developed based on third-order nonlinear phenomena. They can be roughly cast into three main categories;

a) Interferometric schemes in which the generation of a nonlinear phase shift between the individual light beams propagating in an interferometer (e.g a Mach Zehnder) permits intensity dependent switching of the light at the interferometer output[1,2,3].

b) Polarimetric schemes in which the effects of CPM between individual polarisation components of light in a birefringent fibre induce a change in polarisation state at the end of the fibre with input light intensity. The polarisation change can be converted to an amplitude modulation by passing the fibre output through a quarter-wave plate and a polariser combination set to minimise light throughput at low input intensities[4,5].

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c) Intermodal switching schemes using a device such as a directional coupler in which the conventional linear coupling between the individual fibre modes is detuned by the nonlinear response of the material[6,7].

The power levels required to obtain maximal switching contrast are determined by the precise design and details of the system but can be roughly estimated from the relation

$$IL = 500 \qquad (1)$$

where I is the optical power in Watts and L the interaction length in metres. It can be seen from Eqn. (1) that either high power levels or long interactions lengths are required to get appreciable switching effects. In order to obtain switching powers commensurate with any practical optical communication system i.e. $< 1W$ we require switches with correspondingly long interaction lengths ($L > 500m$). Such long interaction lengths lead to severe problems with environmental stability for any devices of the types noted above owing to the difficulty of maintaining a phase balance between the two optical paths (fibre, polarisation or modal) involved. However, if we adopt a scheme based on the fibre Sagnac interferometer (see Fig. 1) in which the two 'arms' of the interferometer are within the same piece of fibre, the system will be inherently stable to perturbations of the system, provided that they occur on a time scale which is long compared to the time taken for light to travel through the interferometer, typically a few microseconds. Since the linear Sagnac interferometer returns light to the port from which it came, it is frequently referred to as a 'loop mirror'.

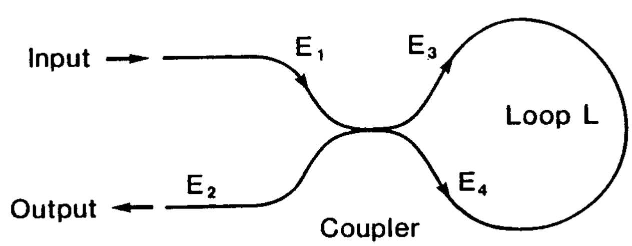

Fig. 1 Schematic of the Non-Linear Optical Loop Mirror (NOLM)

<u>2.1 The Nonlinear Loop Mirror</u>

The switching and pulse shaping potential of the Nonlinear Optical Loop Mirror (NOLM) (see Fig. 1) was first pointed out in 1987 [8,9]. We consider first the case of single-wavelength switching in the regime in which dispersive effects can be neglected (quasi-CW regime). The nonlinear response of the system can be obtained by evaluating the response of the coupler (with asymmetric power splitting α:1-α) to light incident at port 1 (electric field intensity E_1, optical power I_1).

$$E_3 = \sqrt{\alpha} E_1 \qquad (2)$$

$$E_4 = i\sqrt{(1-\alpha)} E_1 \qquad (3)$$

Where electric fields E_1-E_4 are defined in Fig. 1. Calculating the nonlinear phase shift generated by each of the counterpropagating fields E_3 and E_4 during their transmission around the loop of length L, we obtain

$$E_3=\sqrt{\alpha}E_1\exp\left(i\frac{\alpha n_2 I_1 kL}{A}\right) \tag{4}$$

$$E_4=i\sqrt{(1-\alpha)}E_1\exp\left(i\frac{(1-\alpha)n_2 I_1 kL}{A}\right) \tag{5}$$

where n_2 is the nonlinear refractive index, k the propagation vector and A the effective mode area. Evaluating the response of the coupler to the returning counterpropagating beams gives the following expression for the output light intensity I_2:

$$I_2=I_1[1-2\alpha(1-\alpha)(1+\cos\left(\frac{(1-2\alpha)n_2 I_1 kL}{A}\right))] \tag{6}$$

A typical plot of the switching characteristic given by this expression is shown in Fig. 2.

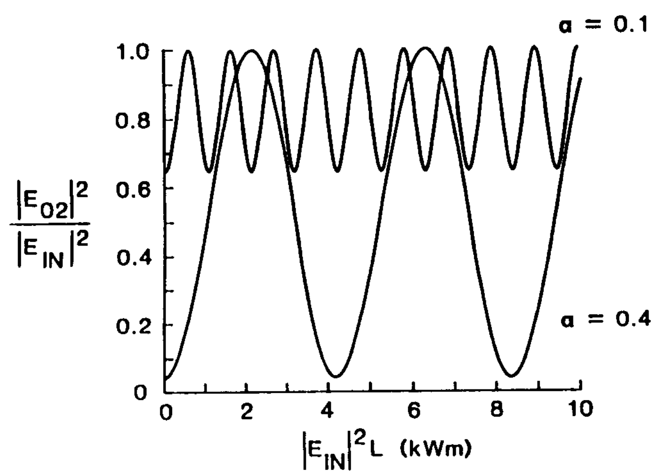

Fig. 2 Intensity response of the NOLM in the square pulse regime. Calculated for two values of α, assuming $n_2=3.2\times10^{-16}$ cm^2/W, A=30 μm^2, λ=1.55 μm and L=1000m [9].

The principal points to note are that the loop reflectivity initially decreases with intensity and that 100% of the power is output at port 2 whenever,

$$I_1=\frac{A(2m-1)\pi}{(1-2\alpha)n_2 kL} \tag{7}$$

where m is an integer. The second point to note is that the minimum output power at port 2 is given by

$$I_2=I_1(1-4\alpha(1-\alpha)) \tag{8}$$

Thus high values of on-off contrast can only be obtained when the value of α approaches 0.5. Unfortunately, (Eqn. (7)) the switching power required increases correspondingly and is infinite at $\alpha=0.5$, since when equal optical power is present in the counterpropagating beams no nonlinear phase delay can develop. Full contrast switching is therefore not possible in this scheme owing to the requirement of asymmetric coupling at the loop coupler. Full-contrast switching can however be obtained in a dual-wavelength NOLM switch, by using a coupler whose splitting ratio is wavelength dependent, $\alpha=0.5$ at the signal wavelength and (ideally) $\alpha=0$ at the pump wavelength. CPM between the signal and the pump results in the generation of a nonlinear phase difference between the counterpropagating components of the signal and leads to switching at the interferometer output[14].

An additional point to note is that in this quasi CW regime, that we have analyzed here, the degree of switching for a given fixed loop length is power dependent, with the transfer function given by Eqn. (6). Therefore passing a pulse with a given intensity profile through the device leads to strong pulse-shaping effects, as is shown in Fig. 3, where a 15nsec, 10W, Q-Switch pulse from a Nd^{3+} doped fibre laser undergoes pulse-narrowing (by a factor of 1.7) on transmission through a 30m loop mirror. This pulse-shaping can lead to quite severe energy loss on switching for a Gaussian pulse. It should be evident the pulse shape which experiences minimum energy loss is square, with a peak power given by the maximum switching-contrast power.

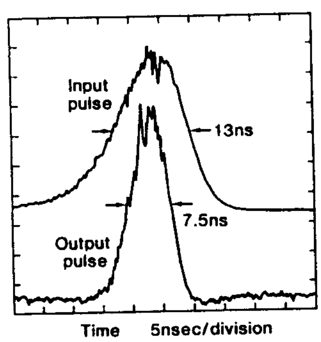

Fig. 3 Pulse-width reduction using a Sagnac loop. The switched pulses were from a Q-switched, Nd^{3+} doped fibre laser. The pulse peak power was 10W and the NOLM loop of length 30m. A pulse narrowing factor of approximately 1.7 was obtained.

In deriving Eqns. 2-8 we have assumed that the light remains in a linear state of polarisation throughout its traversal of the interferometer. However, unless all polarisation maintaining PM components are used in the NOLM this is unlikely to be the case and the NOLM loop is almost certain to possess a degree of birefringence. The influence of fibre birefringence on NOLM behaviour has been considered by Mortimore[10] and it can be shown that the net effect is to add what can effectively be considered as a linear phase-bias to the nonlinear phase shift, i.e. the bias shifts the switching characteristic with respect to the intensity origin in Fig. 2. By appropriate birefringence control (corresponding to a linear phase shift of π) the NOLM switching characteristic can be completely reversed i.e the loop reflectivity can be made to increase with intensity. This ability to phase bias the NOLM is important in many applications. However, the sensitivity of the NOLM response to loop birefringence can lead to severe problems with system stability, since the birefringence is dependent on both temperature and fibre configuration.

If we use the NOLM to switch pulses with durations of the order a few tens of picoseconds or less, dispersion starts to play an important role and its effects need to be included in any calculation of the switch response. The problem involves solution of the normalised Nonlinear Schrodinger equation[11],

$$i\frac{\partial u}{\partial z}+\frac{1}{2}\frac{\partial^2 u}{\partial^2 \tau}+u|u|=0 \tag{9}$$

for the pulse intensity envelopes as they propagate around the loop, i.e. Eqns. 3,4 are no longer appropriate (u, the normalised pulse intensity, in Eqn. (9) is directly proportional to the real pulse intensity envelopes[11]). In general, the effects of dispersion are detrimental to the operation of the switch[8]. However, in the anomalous dispersion regime of the fibre, there are solutions to Eqn. (9) which lead to pulse propagation with characteristics suitable for NOLM switching. These analytic solutions are the well known soliton pulses of the initial form $u(z,t)= N\ \mathrm{sech}(t)$, with N an integer. For N=1 the solution is

$$u(z,t)=\exp(iz/z_0)sech(t) \tag{10}$$

where z_0 is the soliton period and P_1 the peak power (in real units) given by:

$$z_0=0.322\frac{\pi T_{FWHM}^2}{2|\beta_2|} \tag{11}$$

$$P_1=\frac{3.11|\beta_2|}{\gamma T_{FWHM}^2} \tag{12}$$

where β_2 is the dispersion, T_{FWHM} the pulse width and $\gamma=n_2k/A$. Note that since the pulse width and peak power are related the fundamental soliton pulse energy in a given fibre is fixed. The soliton is a unique pulse in which the effects of dispersion and SPM exactly balance, leading to a pulse shape which does not change as it propagates. For our purposes the most important feature of Eqn. (10) is that there is an overall phase factor which applies across the entire pulse envelope and it is this unusual attribute (shared only by the square pulse) that permits low energy-loss soliton switching in the NOLM.

Higher order ($N>1$) soliton solutions show progressively more complicated behaviour as they propagate, but have the feature that the pulse shape evolves periodically with distance, the shape repeating at the soliton period. However, these solutions also have the property of a uniform phase shift profile across the pulse envelope and once again are suited to switching.

The case of soliton pulse propagation with non-integer N has been considered by Doran et al[8]. Their results show that such pulses still generate reasonably uniform phase shifts across their envelope and are suitable for switching. This is an important point, since as noted earlier the NOLM relies on asymmetric counterpropagating power levels around the loop in order to generate a net phase difference i.e. at least one of the pulses is not a fundamental soliton on its propagation around the NOLM loop. The soliton energy switching characteristics of a NOLM are shown in Fig. 4, were it is seen that low switching losses can be obtained. Solitons appear to be the natural units for NOLM switching schemes.

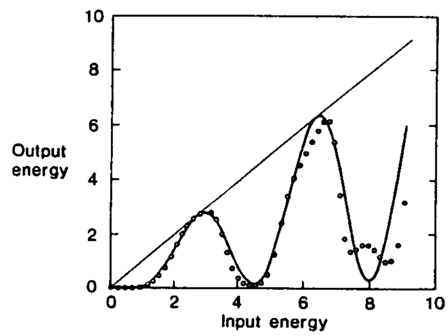

Fig. 4 Typical NOLM soliton switching characteristic for $\alpha=0.4$. The units are in terms of the energy of a single soliton; the conversion to real energies depends on the assumed pulse duration. For example, a 7psec soliton has an energy of 2pJ for the parameters adopted (see Fig.2)[9].

Soliton switching has been demonstrated experimentally by a number of authors and >90% energy switching efficiency obtained[12,13]. Dual-wavelength switch operation has also been investigated using the NOLM in both conventional[14,16] and polarisation-maintaining, dispersion-shifted fibre[15]. Pulse demultiplexing[17], optical-sampling[18] schemes and simple logic elements[19] have also been demonstrated.

2.2 The Nonlinear Amplifying Sagnac Switch (NALM)

Although the NOLM has proved itself a fast and efficient optical switch for single-wavelength operation, it does not permit 100% switching contrast and requires high input power levels (or long loop lengths) to obtain switching. A recent development which can circumvent most of these problems, has been to incorporate an amplifier within the NOLM[20,21], as shown in Fig. 5. Since the amplifier is located at one end of the loop, the counter-clockwise propagating light traverses the loop at lower intensity than the clockwise propagating light. Thus the NALM coupler can be set at $\alpha=0.5$ with the amplifier providing the asymmetry.

Considering once again quasi-CW operation and assuming an amplifier gain G and an effective fibre path-length L, the net phase difference between counterpropagating pulses can be written as

$$\Delta\phi=(G-1)n_2 I_1 kL \qquad (13)$$

Thus the output light transmitted by the system is given by:

$$I_2=GI_1\sin^2(\Delta\phi) \qquad (14)$$

giving full amplitude switching at $\Delta\phi=(2n+1)\pi$, n=0,1,2. The high gain available with erbium-doped fibre amplifiers (G>40dB) thus reduces input switching powers from the watt to the microwatt regime. The other point to note is that the NALM has inherent gain which has potential for use as a mode-locking element within a laser cavity.

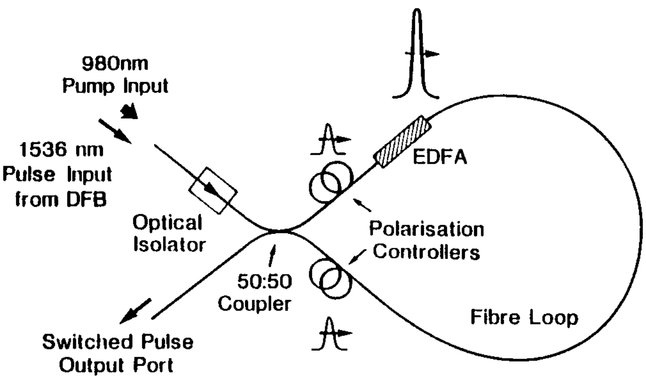

Fig. 5 Schematic of the Nonlinear Amplifying Loop Mirror (NALM).

The input/output power transfer characteristic for a high gain (46dB) reverse-biased NALM is shown in Fig. 6. The loop length was 306m and the input signal source a DFB laser operating at a wavelength of 1536nm. Low threshold NALM switches have also more recently been developed based on the highly nonlinear, semi-conducting amplifier[22,23]. The operation of the NALM in the soliton regime has also been analyzed for a relatively low-gain system (of the order 3dB) by Fermann[20], who concludes that solitons should be well switched by the NALM.

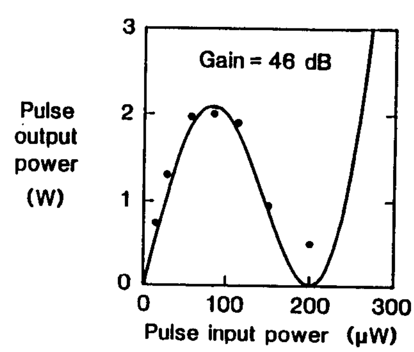

Fig. 6 The NALM switching characteristic at high gain (G=46dB). The NALM loop of length 306m was set to reverse bias by birefringence control.

3. PASSIVE MODE-LOCKING USING NONLINEAR SWITCHES

The majority of work concerned with short-pulse generation in fibre lasers has concentrated on active mode-locking with either fast phase- or amplitude-modulators[24,25,26]. However, as is well known in bulk laser theory, the incorporation of nonlinear elements such as saturable absorbers within a laser cavity can lead to passive mode-locking of the system and generally yields shorter pulses[27]. In the last few years several passive schemes based on fibre nonlinearities have been reported[28,39,30]. With the exemption

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of ref 28 these schemes required active modulation in order to initiate mode-locking. Particularly impressive is the work of Hofer et al[28] who have succeeded in generating pulses as short as 50fs using a polarisation-switching scheme and precise dispersion control.

Provided that they are biased using birefringence, the NOLM and NALM characteristic on the first switching cycle is similar to that of a saturable absorber, a nonlinear element which is well known to produce Q-switching and mode-locking in lasers. In fibre lasers the first experiments on passive nonlinear mode-locking were performed by using a Sagnac loop as an end mirror in a Fabry-Perot cavity[31]. Birefringence control was required to set the NOLM reflection characteristics to the desired nonlinear response, i.e. increasing reflectivity with increasing intensity (up until the first switching maximum). The system could be made to mode-lock either by the injection of intense optical pulses, or by mechanically perturbing the system. Generation of square pulses with durations as short as 100 psec were reported, although structure on a femtosecond time scale was observed. Folowing on from these encouraging preliminary experiments, a more complex scheme, known as the Figure-8 laser[32,33,34] has generated far shorter, bandwidth-limited pulses.

3.1 The Figure-8 Laser

The Figure-8 laser scheme is shown in Fig. 7. The system consists of two discrete loops, one a unidirectional ring cavity and the other a NALM loop. At low intensity, light incident at port A is reflected back to port A and is ultimately lost within the isolator. However, as the light intensity increases the NALM starts to transmit and light passes to port B. Light is now able to circulate within the isolator loop, providing feedback for the laser.

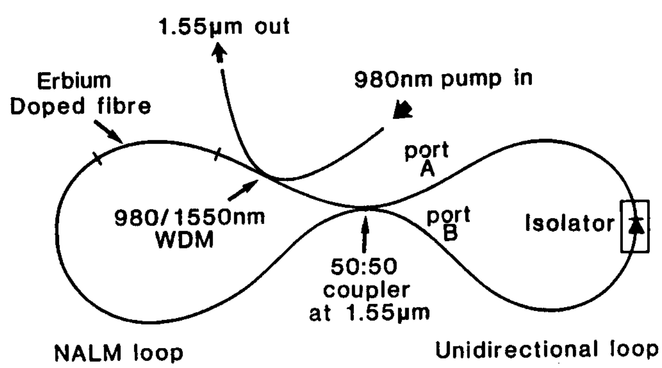


Fig. 7 Experimental configuration of the self-starting, passively mode-locked fibre laser.

If we consider light propagation in the quasi CW regime, then the cavity loss versus light intensity has the form shown in Fig. 8, where it is seen that there is a well-defined intensity which produces minimum laser resonator loss. Since the laser system will always seek to operate in a mode which minimises internal losses, it favours high-intensity, pulsed operation. The minimum-loss pulse waveforms will either be square pulses with a peak intensity defined by the switching power of the NALM, or solitons. Recall that both of these waveforms have the characteristic that they generate uniform nonlinear phase profiles across their entire pulse envelope and can therefore switch without loss in a NOLM or NALM. Furthermore, the low input powers required to switch a NALM operating at high gain enables the pulsed operation to build up from noise at the NALM input. The process is assisted by allowing a degree of CW lasing at low input powers, either by using a coupler with an asymmetric coupling ratio, or by biasing the NALM by means of birefringence.

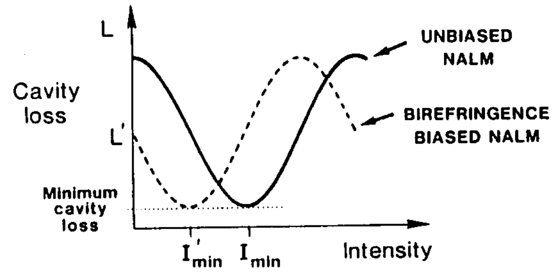


Fig. 8 Cavity-loss characteristic as a function of intensity for pulses in the square-pulse regime.

The Figure-8 laser is found to undergo a variety of different types of pulsed behaviour[38]. Both square-pulse[32,35] and soliton pulse generation[36,37] have been observed with the system operating at 1.56 microns. The square pulses are relatively long in duration (see Fig. 10), the shortest so far observed were 150 psec. The most striking feature of the pulses is their broad optical bandwidths, sometimes as large as 35nm, and therefore they are far from transform limited. On the other hand, when solitons are generated they are very much shorter in duration and are transform-limited. The shortest pulses so far observed have a duration of 320fsec [36,37]. The autocorrelation trace and optical spectra obtained in this case are shown in Fig. 9. Note the large blue-shifted component of the spectra, the origin of which is believed to be due to splitting of the pulse into soliton and non-soliton components during the amplification and propagation processes[39]. These components separate both temporally (the non-soliton pulse also broadens rapidly) and spectrally, as the soliton pulse gets red shifted by the soliton self-frequency shift[11]. A dynamic balance between the self-frequency shift and the gain-pulling effect of the amplifier push the pulse out to the long-wavelength edge of the erbium gain-spectrum. The large blue-shift component is not observed when generating solitons with durations greater than approximately 600fsec, although small additional spectral features (small side lobes) reminiscent of modulational instability are observed.

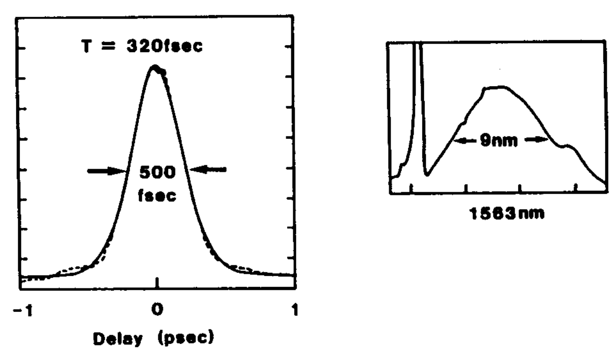


Fig. 9 Background free auto-correlation trace and optical spectra of 320 femtosecond soliton pulses. The solid line autocorrelation profile represents a non-linear least-squares fit to the experimental data on the assumption of a soliton pulse-form.

As well as having two distinct modes of pulse generation (square and soliton), the Figure-8 laser 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. The effect is illustrated in Fig. 10.

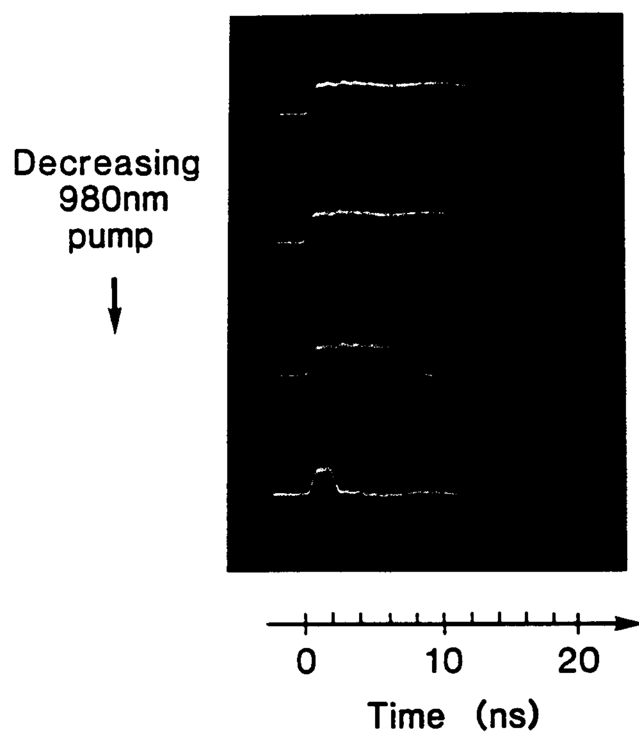


Fig. 10 **Output pulse shapes for 104m mode-locked fibre laser as a function of pump power. Input 980nm pump powers were (a)155mW, (b)115mW, (c)75mW and (d)40mW. The system self-started at an input pump power of 80mW.**

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 repeating at the cavity round-trip frequency. The situation is illustrated in Fig. 11. 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 coherence 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 100GHz (as determined from autocorrelation scans) have been observed within the pulse bunches.

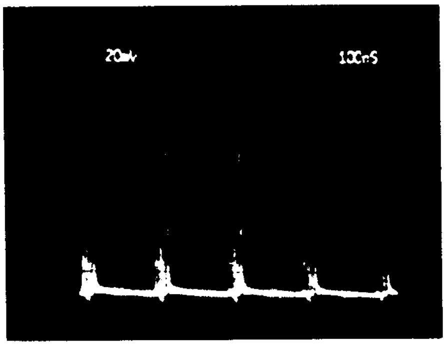


Fig. 11(a)Soliton pulse bunches circulating around the cavity at the cavity round-trip frequency.

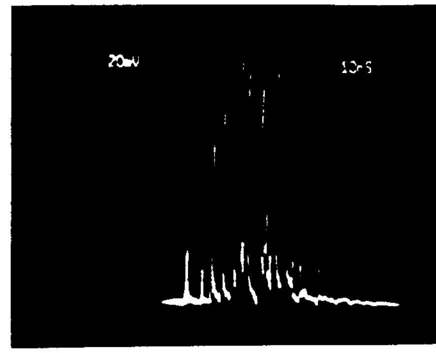
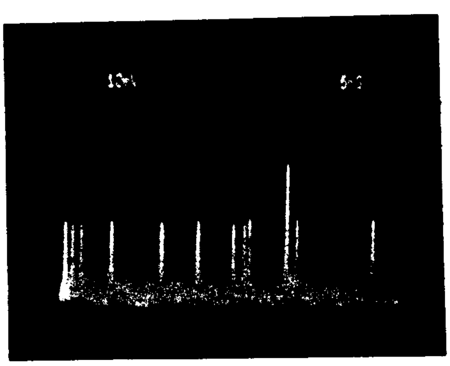


Fig. 11(b) Exploded view of an individual soliton bunch

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 Fig. 12a, where, since the detector response time (55psec) is far longer than the pulse duration (500fsec), the trace effectively displays the pulse energy. The pulse with twice the amplitude of the others is due to two pulses occurring 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.



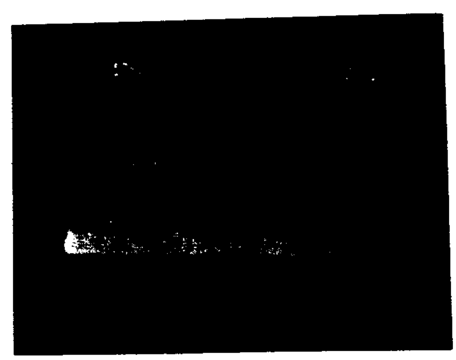


Fig. 12 450fsec soliton pulse trains.

Fig. 12(a) Pulses randomly spaced but well separated. The pulse of apparently twice the the amplitude of the others is due simply to two pulses arriving within a time period less than the detector response time.

Fig. 12(b) Pure passive, harmonic mode-locking (f=67.2MHz, the 16 harmonic of cavity round-trip frequency.

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 Fig. 12b. 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 counterpropagating pulse bunches within the NALM loop can play a significant role in its switching operation. The effects of cross-phase modulation would be minimised for tightly-bunched pulse trains.

In order for the Figure-8 laser to become a practical soliton source the problems of stabilisation of the soliton repetition rates and environmental stability need to be addressed. Repetition rate stabilisation by means of active modulation and/or pulse multiplication schemes are currently being investigated.

The Figure-8 laser is based on the switching characteristics of a non-birefringence biased NALM and could therefore be constructed from polarisation maintaining components. This would greatly improve the stability of the system. However, all previous experiments have been performed with conventional single-mode fibre devices in which the state of bias of the NALM has been both ill-defined and has been used to toggle between the different operating modes of the laser. It should be noted from Fig. 8 that the rate of change of cavity loss with intensity is zero for the start-up condition (I=0) for an unbiased NALM, which may hinder the onset of the pulsed mode of operation in an all PM system. However, we have recently constructed an all PM component laser and have found that the system will indeed self-start and is environmentally stable.

4. CONCLUSION

The all-fibre NOLM and NALM switches have great potential both as all-optical soliton-processing elements. When included within fibre laser cavities they act as soliton generating nonlinear elements. These switches and lasers will be key elements in any future soliton-based telecommunication scheme.

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