of many C=O and C=C bonds as indicated in the FT-IR spectrum. Because the existence of N—H bonds is found in

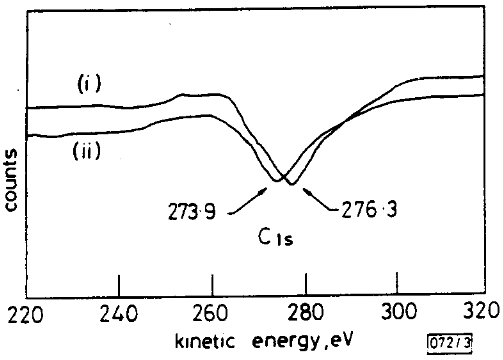

Fig. 3 *Carbon (KLL) Auger electron spectra of untreated and N_2 plasma treated PBS*

N_2 plasma conditions are same as Fig. 2
(i) N_2 plasma treated PBS
(ii) Untreated PBS

the FT-IR spectrum, there is also the formation of C—N bonds. Therefore, a core electron of carbon is shifted to a higher binding energy due to the carbon atom becoming more electropositive. Consequently, a corresponding chemical shift in the Auger electron kinetic energy is observed.

The ESCA analysis also indicates the existence of a significant amount of nitrogen with a binding energy of 398·9 eV in the N_2 plasma treated PBS. It would therefore appear that a nitrogen atom is clearly involved in the new bond formation of the hardened chemical composition of PBS. The glass transition temperature (T_g) of PBS is increased by about 10°C as shown in Fig. 4 and indicates that a certain degree of crosslinking occurs in PBS after N_2 plasma treatment.

The reduction of positive or negative resist flow during postbake as a result of N_2 plasma pretreatment has been

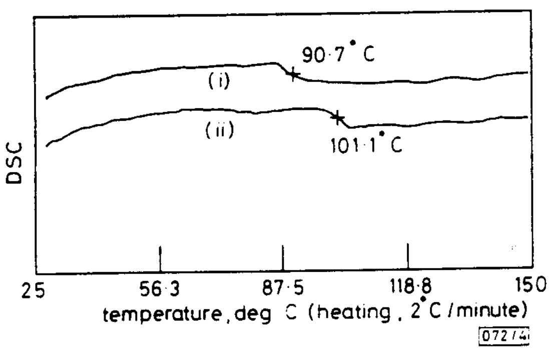

Fig. 4 *Differential scanning calorimetry (DSC) measurements showing glass transition temperature (T_g) of untreated and N_2 plasma treated PBS*

N_2 plasma conditions are same as Fig. 2
(i) Untreated PBS
(ii) N_2 plasma treated PBS

reported.[5] The creation of a hardened shell at the surface is suggested. In our study, although the natures of the chemical reactions responsible for these enhanced RIE resistances after N_2 plasma treatment are not fully known, it is believed that the crosslinking of PBS molecular chains is the most important cause. Depolymerisation of PBS is inhibited or retarded. Surface modification of PBS by the formation of some RIE resistant functional groups is also postulated.

Conclusions: Enhancement of CF_4 and N_2 RIE resistance of PBS by N_2 plasma pretreatment has been demonstrated. The original thickness of PBS can be maintained. Further study is needed to clarify the chemical composition and mechanisms involved.

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SELFSTARTING, PASSIVELY MODELOCKED ERBIUM FIBRE RING LASER BASED ON THE AMPLIFYING SAGNAC SWITCH

Indexing terms: Lasers, Optical fibres, Nonlinear optics

A novel self-starting, passively mode-locked erbium fibre laser is reported. The scheme is based on the reflection properties of a nonlinear amplifying loop mirror and provides a stable source of picosecond pulses.

Nonlinear optical loop mirrors (NOLMS)[1] are of considerable interest for optical switching and modelocking of fibre lasers. Reverse biased NOLMS[2] have already been incorporated in conventional active modelocking systems to act as intracavity pulse compressors* and also as all-fibre passive modelockers.[3] However, in such systems the requirement for loop biasing by means of induced fibre birefringence leads to polarisation control problems and hence to environmental instability. Recently, nonlinear amplifying loop mirrors (NALMS)[4,5] have been shown to offer improved pulse switching properties both in terms of input switching power (full amplitude switching powers as low as 200 μW have been reported)[4] and on/off contrast. We report on the use of a unbiased NALM in an all-fibre, self-starting, passive modelocking configuration. We believe this development will lead to remarkably simple, stable and practical sources of picosecond pulses at 1·55 μm for soliton communication systems.

The laser configuration is shown in Fig. 1. At low input powers the NALM acts as a conventional loop-mirror reflecting light back to the port from which it came. Thus low intensity light circulating anticlockwise in the isolator loop

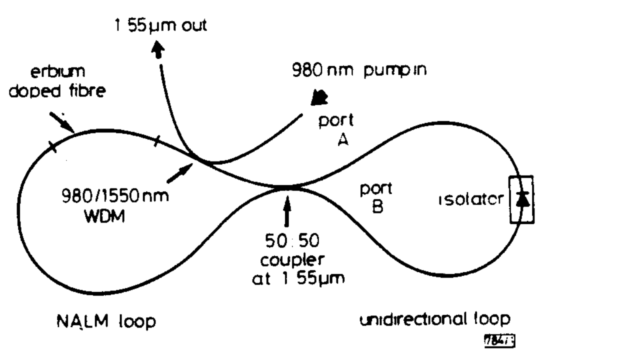

Fig. 1 *Experimental configuration of selfstarting, passively modelocked fibre laser*

* FERMANN, M. E., *et al.*: 'Active mode-locking of a fibre laser incorporating a nonlinear loop mirror', submitted to *Optics Letters*

enters the NALM at port A and is reflected back to the same port, i.e. towards the isolator, where it is lost. As the intensity of light incident at port A is increased, the loop becomes nonlinear and light is switched to port B, whereupon it circulates counterclockwise in the isolator loop. In this instance the light passes through the isolator and provides feedback to the gain medium. The system thus experiences lowest loss for high light intensities and is therefore biased to operate in a pulsed mode. The S-shaped switching characteristics of the NALM are described in References 4 and 5. The minimum loss switching pulses are either rectangular with a peak intensity determined by the switching power of the loop or solitons which develop a uniform phase over the entire pulse envelope as they propagate and can thus be fully switched.[1] Furthermore, the low input powers required to switch an NALM operating at high gains means that pulsed operation is able to build up from noise at the NALM input. Control of the self start process is provided either by introducing a slight phase bias in the NALM loop or by arranging for asymmetric coupling at the NALM coupler.

The experimental configuration employed a loop coupler arranged to give 50 : 50 coupling at 1550 nm. The unidirectional isolator loop had a total length of 2 m. The isolator was polarisation insensitive, with an insertion loss of 0·4 dB and an isolation of 40 dB. The doped fibre was 2 m long and contained 800 ppm Er^{3+} ($\lambda_c = 1230$ nm, $NA = 0{\cdot}14$). A 980/1550 WDM coupler was inserted into the NALM to permit pumping of the amplifier and to provide output coupling (0·5%). The remainder of the NALM loop was constructed from single-mode fibre having $\lambda_c = 960$ nm, $NA = 0{\cdot}15$ and $D = 5$ ps/nm/km. Using a Ti : sapphire pump laser at 980 nm, the system properties were investigated for total NALM loop lengths of 12 m and 102 m. The total round trip loss of the system was ~4 dB in both cases. As the laser's operation is based on an unbiased NALM, the system could in principle be constructed from all-polarisation-maintaining fibres, resulting in complete environmental stability. However, as a first demonstration we have used conventional fibres, and therefore polarisation controllers were required in both the unidirectional and NALM loops.

In operation it was found that the laser passively modelocked at the cavity round trip frequency once a certain input pump power level was reached (~100 mW for 104 m, ~200 mW for 14 m), although when mode locked, the input pump power to the system could be reduced well below the power required for selfstarting. When CW modelocking the system lased at 1·55 μm. At low pump powers and for certain loop birefringence settings, a self Q switch, modelocked lasing regime was encountered. In this regime the lasing wavelength shifted to 1·53 μm. This wavelength shift is associated with the change in cavity loss due to the change in loop bias.[6] The CW modelocked pulses were in general rectangular. The S-shape switching characteristic of the NALM causes the laser cavity loss to decrease progressively with pulse amplitude until a certain point is reached, when it starts to increase again. Thus the power of the internal circulating pulse is clamped to this peak value and its width must increase to accommodate a higher average circulating power. The effect is shown in Fig. 2 for the 104 m system where the pulse is seen to narrow as pump power is decreased. The shortest pulses generated with the 104 m system were 500 ps with a circulating peak power of 10 W and at a repetition rate of 2 MHz. On going to the 14 m system, the narrowest pulses obtained were 150 ps FWHM (see Fig. 3) at a repetition rate of 16 MHz. In this case the internal circulating peak power in the isolator loop was estimated at 100 W, which is close to the calculated nonlinear switching power of the loop. Autocorrelation traces of these pulses gave some indication of pulse substructure on a femtosecond time scale, this is thought to be due to the effects of modulational instability.

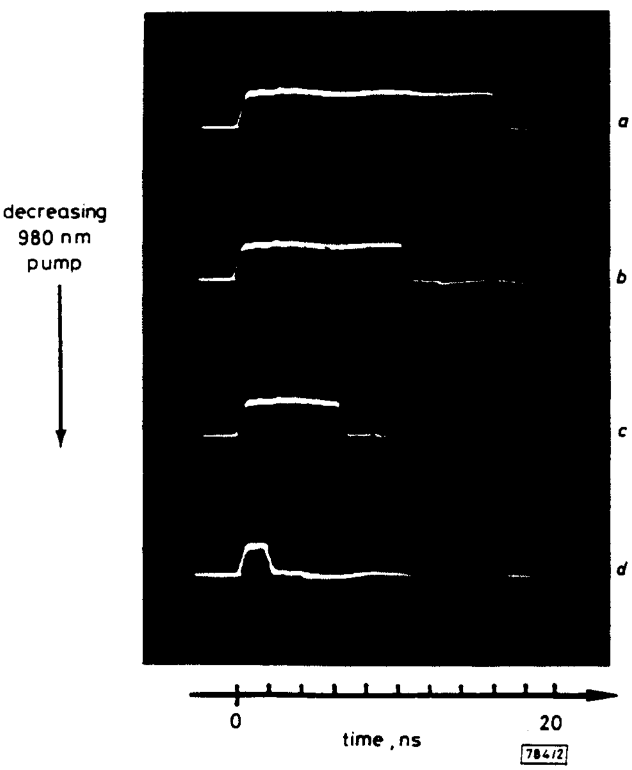

Fig. 2 *Output pulse shape for 104 m modelocked fibre laser as function of pump power*

Input 980 nm pump powers were (i) 155 mW, (ii) 115 mW, (iii) 75 mW, (iv) 40 mW

System self started at an input pump power of 80 mW

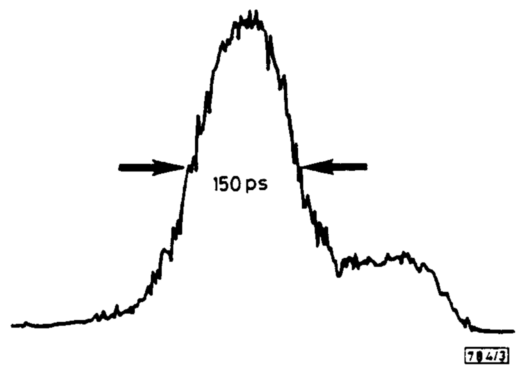

Fig. 3 *Pulse output from 14 m modelocked fibre laser*

The observed pulses were not bandwidth limited, since the optical spectra associated with the generated pulses were extremely broad (> 8 nm) and showed periodic modulation at a 1 nm scale. This spectral modulation is thought to be due to birefringence, or etalon effects associated with the isolator. Replacing the isolator with a polarisation sensitive device enabled bandwidth-limited soliton pulses, with half-width as short as 320 femtoseconds, to be generated. However, within this soliton regime the pulse repetition rates become highly unstable, with bunched soliton pulse rates as high as 30 GHz. The soliton regime of operation is described in detail elsewhere.†

These experiments clearly demonstrate the potential of the figure-eight selfstarting, modelocked fibre laser configuration. Further improvements are expected with the use of polarisation-maintaining components and the addition of a pulse multiplier (e.g. a Fabry-Perot) to stabilise the soliton pulse repetition rates.

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SUBPICOSECOND ALL-FIBRE ERBIUM LASER

Indexing terms: Optical fibres, Lasers, Nonlinear optics

A nonlinear amplifying loop mirror has been turned into a laser by feedback of the output to the input through a fibre-pigtailed optical isolator. After some optimisation, pulses as short as 314 fs were produced. The pump powers are low enough that laser diodes could be used for pumping.

With the growing interest in erbium-doped fibres for amplifiers in telecommunication systems, there have been attempts to produce high repetition rate, compact modelocked sources based on the gain in this fibre at 1·5 μm.[1,2] The shortest pulses reported to date are those of Smith *et al.*, who produced pulses as short as 1·2 ps using active modulation and soliton formation in a laser which included bulk components.[3] We present a passively modelocked all-fibre erbium laser which produces substantially shorter pulses.

The laser (figure eight laser or F8L) drawn schematically in Fig. 1, is a ring fibre laser with an amplifying pulse shaper in the cavity. A nonlinear amplifying loop mirror (NALM), comprising a 50% fibre coupler, an erbium doped fibre, and a wavelength division multiplexer pump coupler, was used as the pulse shortening and gain element.[4] The output of the NALM was connected to an output coupler and then to a pig-tailed optical isolator. The output of the isolator was fed into the input of the NALM.

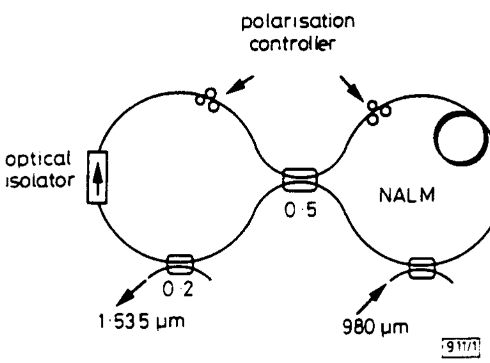

Fig. 1 *Experimental layout of F8L*
Components are all commercially available

The operating characteristics of the F8L will be determined by the properties of the fibre, and the switching behaviour of the NALM. Because the laser operates beyond the zero dispersion point of the fibre, the possibility of optical soliton propagation is present. The peak power of the fundamental soliton is given by the equation

$$P_1 = \left(\frac{0{\cdot}776\lambda^3}{\pi^2 c n_2}\right)\frac{|D|A_{eff}}{\tau^2} \qquad (1)$$

where P_1 is the peak power, $|D|$ is the fibre dispersion, n_2 is the nonlinear index, λ is the signal wavelength, A_{eff} is the effective fibre area and τ is the pulse width.[5] In addition, the switching power of the NALM is given by

$$P_s = A_{eff}/n_2 L(g-1) \qquad (2)$$

where L is the length of the fibre, and g is the optical gain.[4] Because a soliton is transmitted with the least loss through a nonlinear mirror, a good guess for the operating point of the F8L would be $P_s = P_1$ or

$$\tau^2 = \left(\frac{0{\cdot}776\lambda^3}{\pi^2 c}\right)|D|L(g-1) \qquad (3)$$

where it is apparent that a reduction in loop length should produce shorter pulses.

Previously this laser has produced pulses as short as 2 ps.[6] The nonlinear fibre length was 30 m and transform limited pulses were observed. When the fibre length was reduced to 2 m, the bandwidth was seen to increase, but shorter pulses were not immediately observed.

On re-examination of the pulses, it could be seen that as a function of power, different autocorrelation traces could be obtained. These traces are shown in Fig. 2. Their shape corresponds well to the experimental and theoretical results of Smith *et al.* for pulse shaping in a passive nonlinear loop mirror. This correlation indicates that the pulse circulating in the laser is broadening in its trip through the laser and is being shaped by the nonlinear mirror. In addition, the peak of the pulse is seeing a phase shift greater than that required for complete switching. As a result of this observation the nonlinear fibre was shortened by an additional 80 cm to a length of approximately 1·2 m.

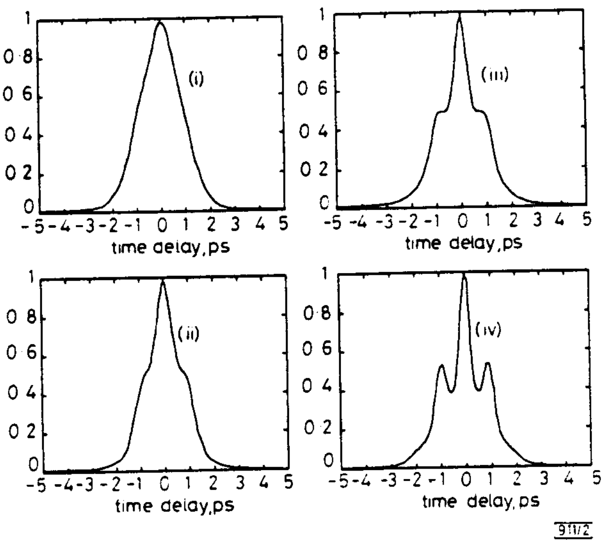

Fig. 2 *Autocorrelations of F8L output for 2 m nonlinear fibre length for increasing power*
Power increased from (i) to (iv)

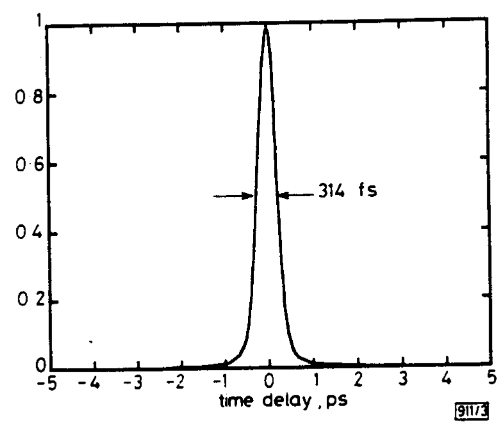

Fig. 3 *Autocorrelation of F8L output for nonlinear fibre length of 1·2 m*
Pulse width = 314 fs assuming $sech^2$ pulse shape