acoustic paths. In the first simulation, a sinusoidal signal with frequency at 2300 Hz and SNR equal to 20 dB was used to compare the convergence rate of the new algorithm and the traditional algorithm [3]. The initial value of w was 1·5, corresponding to a centre frequency of 800 Hz. The adaptation step size was 0·1 for both algorithms. The mean-squared error (MSE) output of the adaptive notch filters from the two algorithms are plotted in Fig. 4. It is shown that systems with adjustable pole radii, controlled by the new lock/unlock algorithm, converge more quickly than those with a fixed radius.

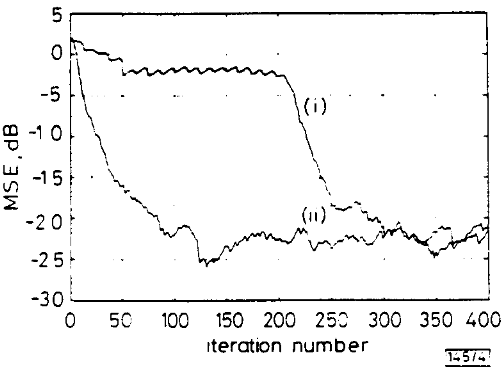

Fig. 4 *Learning curves*

Initial $w = 1·5$, adaptation step $\mu = 0·1$, pole radius $r = 0·85$ for fixed algorithm, and $r_{min} = 0·5$, $r_{max} = 0·95$ for new algorithm
(i) fixed pole radius
(ii) variable pole radius

The performance of howling control can be evaluated in terms of the howling margin enhancement (HME). The howling margin is defined as the minimum attenuation insertion required without initiating howling. Therefore, the HME is the difference between the howling margins obtained with and without the adaptive howling control unit; i.e.

$$HME = M - M_0 \qquad (9)$$

where M_0 is the howling margin of the basic system without the howling control.

Table 1 summarises the simulation results for HME at different frequencies. Digitised speech signals were used as the input to the system. Results indicate that HMEs of 8–14 dB are achieved by this simple technique.

Table 1 HOWLING MARGIN ENHANCEMENT RESULTS FROM SIMULATION

Normalised frequency	HME
	dB
0·125	12
0·238	14
0·275	10
0·325	8

Conclusion: The howling effect in a speakerphone system was studied in terms of the frequency response of acoustic and hybrid paths. A new second order IIR adaptive filter was developed to improve the convergence rate and was implemented into the speakerphone system. Results indicates that this technique is very effective in eliminating howling. This technique has the advantage of less computation and fast convergence. Furthermore, this algorithm with parallel combinations of IIR filters may be applied to the howling control of multimicrophone systems where howling at two or more frequencies at a time is possible.

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Nd : YAG LASER PUMPED PICOSECOND Yb^{3+}/Er^{3+} FIBRE LASER

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Indexing terms: Optical fibres, Lasers

A 1064 nm pumped Yb^{3+}/Er^{3+} fibre laser, actively mode-locked using a selfresonant Raman-Nath modulator is described. With 300 mW of pump power the laser produces 1·7 ps pulses with peak powers as high as 200 W at a repetition rate of 82 MHz. Overall pump/signal transfer efficiencies greater than 30% have been obtained.

The unique combination of an active medium, nonlinearity and negative group velocity dispersion make erbium-doped fibres extremely attractive as the basic component of fibre soliton lasers [1, 2]. Recently, greatly improved performance in 1·06 μm-pumped fibre amplifiers based on Yb^{3+}-sensitised, Er^{3+}-doped silica fibre have been obtained [3]. This development enables the use of readily-available, high-power, solid-state mini-YAG lasers as pump sources and thus considerably increases the output available from practical fibre lasers. Even more interestingly the 1 W diode-pumped Nd^{3+}-doped fibre laser recently developed in our laboratories can also be employed as a pump source in an all-fibre tandem-pumping arrangement [4]. We report a high-power fibre-laser source based on the new codoped fibre which is capable of generating picosecond pulses with peak power as high as 200 W.

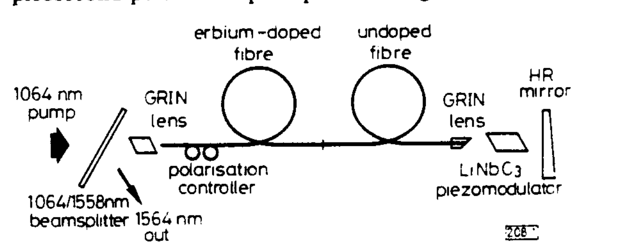

Fig. 1 *Experimental configuration*

The basic experimental setup is shown in Fig. 1. The gain was provided by a codoped fibre ($NA = 0·16$ and $\lambda_{co} = 960$ nm) with a Yb^{3+}-doping level of 7500 *ppm* and 880 *ppm* of Er^{3+} ions. In our initial experiments we concentrated on fundamental mode-locking. The length of the codoped fibre was 1·2 m giving a round-trip time that corresponded to the modulational frequency (82 MHz) of a PS (piezoelectrically-induced strain-optic effect) bulk lithium niobate modulator, similar to that described in Reference 5. A novelty was that the modulator was included in the feedback loop of a simple electrical circuit and was therefore selfresonant at a frequency of 82 MHz, thus removing the need for an external signal generator. The modulator required only a 24 V DC supply and gave a diffraction efficiency of 30%. This value corresponds to a modulation depth $\delta\phi = 1$ [5].

Although pumpable by a mini-YAG laser, for experimental purposes we employed a standard Quantronix-116 Nd^{3+} : YAG laser. Owing to the high gain available and to avoid problems of mirror damage at high pump powers no mirror was used at the pump end of the fibre, feedback being provided by the 4% Fresnel reflection only. Laser output was taken from a dichroic beamsplitter and the fibre rear mirror was highly reflective at the laser wavelength. The rear mirror was mounted on a translational mount to permit fine tuning of the cavity length. Mechanical fibre birefringence controllers were used to set the intracavity polarisation to match the Brewster angled modulator.

In such a configuration the fibre laser generated 20 ps pulses with a spectral bandwidth of 0·15 nm. Peak pulse intensity fluctuations were less than 5%. The operating pump power was 550 mW and yielded an output signal power of 40 mW, giving a 24 W peak power and an overall 7% pump/signal transfer efficiency. Note that the laser performance was relatively insensitive to the setting of the polarisation controllers, and that the relatively low efficiency of this laser configuration is caused by the inability of the required 1·2 m length of codoped fibre to fully absorb the pump.

In accordance with the selfconsistent field theory of active mode-locking [6] (which is applicable for our system because the line broadening can be considered homogeneous), the pulse duration τ_p in the steady-state regime is given by

$$\tau_p = 0{\cdot}45\left(\frac{g}{\delta\Phi}\right)^{1/4} \cdot \left(\frac{1}{f_m\,\Delta v}\right)^{1/2}$$

In our case the gain $g = 1/2\ \ln\ (1/R_{eff}) = 2.03$, the modulation depth $\delta\Phi = 1$, the gain bandwidth $\Delta v = 4{\cdot}5$ THz and the modulation frequency $f_m = 82$ MHz where R_{eff} is the effective cavity loss per round trip. Inserting these values into eqn. 1, $\tau_p = 28$ ps is obtained. The discrepancy with the experimental result indicates that selfphase modulation plays a significant role in the pulse formation process.

To improve the laser efficiency and to increase the strength of the nonlinear effects, the length of the codoped fibre was increased from 1·2 to 5 m and fourth harmonic mode locking attempted, i.e. four pulses within the resonator. With 550 mW pump power the laser produced 70 mW average power at 1563 nm, an increase in efficiency to 13%. However, the autocorrelation traces showed the pulses to consist of a short duration spike (picosecond time scale) sitting on an intense, broad pedestal. Similar behaviour has been observed previously [1, 7] and, in common with these authors, we increased the cavity length of the fibre laser by splicing a further 20 m of a conventional singlemode fibre to the amplifier, giving a total cavity length of 25 m and 20 pulses within the cavity. At a reduced pump power of 300 mW, we then obtained 40 mW output power (14% efficiency). The temporal characteristics of the laser output were very much improved, consisting of a highly-stable, clean train of pulses with a repetition rate of 82 MHz and a pulse duration of 1·7 ps.

A typical autocorrelation trace of the mode-locked laser is shown in Fig. 2, and the corresponding spectrum in Fig. 3.

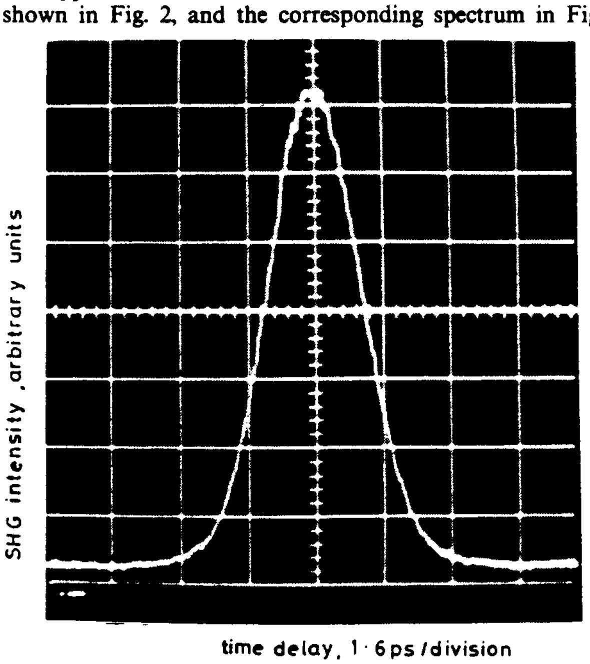

Fig. 2 *Background free autocorrelation trace of 1·7 ps pulses*

The autocorrelation trace shows that the pulse is accompanied by a low-level pedestal, containing approximately 30% of the total energy. The pulse shape is an excellent fit to a $\text{sech}^2\ x$ shape, giving a pulse duration of 1·7 ps and a peak power of 200 W. To our knowledge this value represents the highest output power form a mode-locked erbium-doped fibre laser to date. Decreasing the pump power by 10% and adjusting the state of polarisation enabled removal of the pedestal. However, in this instance the pulse duration rose to 4 ps.

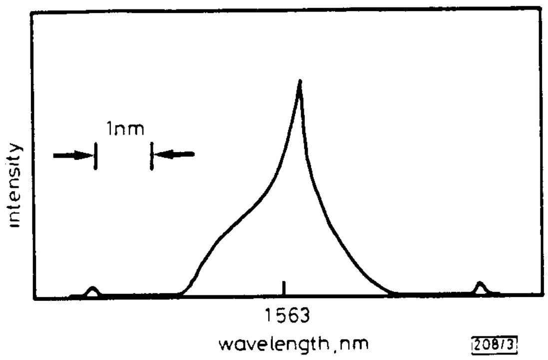

Fig. 3 *Optical spectrum of 1·7 ps pulses*

For our given fibre core area of 70 μm^2 and a group velocity dispersion of +15 ps/nm km, the fundamental soliton of 1·7 ps pulse duration has a peak power of 11 W; we conclude that the laser generates higher-order, solitonic pulses and therefore that the effect of multisoliton pulse compression plays a significant role in the pulse formation process. The output spectrum also has a central peak that can be attributed to the effect of multisoliton pulse compression [8].

In conclusion, we have demonstrated a YAG-pumped mode-locked fibre laser based on codoped Yb^{3+}/Er^{3+} fibres, employing a selfresonant Raman-Nath modulator. The laser is a simple convenient source of high power, transform-limited, ultrashort pulses for applications in advanced optical communication systems, spectroscopy and nonlinear optics studies. It is noted that the system can be pumped by high power AlGaAs diode arrays if an Nd^{3+}, cladding-pumped, fibre laser is used as an intermediary source in an all-fibre, tandem pumping configuration. In recent experiments with improved codoped fibres we have obtained average output powers as high as 200 mW with overall pump-signal transfer efficiencies exceeding 30%. However, the shortest pulses we have obtained so far using this fibre had a duration of 20 ps. Further improvements in both efficiency and minimum pulsewidths are expected.

24th February 1992

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