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Optically-Controlled Wavelength-Adjustable Passively Mode-Locked Erbium-Doped Fibre Ring Laser

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Abstract

An integrated all-fibre technique has been used to implement wavelength tunability in a passively mode-locked erbium fibre ring laser. A smooth, continuous tuning range of 4 nm controlled simply by varying the power of an optical pump beam has been demonstrated.

Passively mode-locked fibre lasers have recently been the subject of considerable study, as they hold out the attractive prospect of an easy-to-use fibre-integrated optical short pulse source. While short pulses have already been demonstrated in various fibre lasers[1-3], the potential of such devices should be further enhanced if their operating wavelength can be easily and accurately adjusted as well, particularly for wavelength-sensitive applications.

Much of the work concerning wavelength control in fibre lasers has been on tuning narrowband fibre lasers, although mode-locked fibre lasers have been reported incorporating bulk tuning elements, such as gratings[4] or bandpass filters[5], and making mechanical adjustments to change the wavelength. A semiconductor Bragg filter has also been used to electronically tune or mode-lock a fibre laser[6], but not both. An integrated all-fibre technique for tuning the wavelength of mode-locked fibre lasers without requiring mechanical adjustments seems highly desirable for the realisation of a compact and rugged fibre short pulse source. The work here demonstrates the possibility of just such a technique, which uses an optical pump beam to position the operating wavelength of the mode-locked fibre laser.

The passive mode-locking technique employed is based on nonlinear polarisation rotation in a unidirectional ring cavity incorporating an isolator (Fig. 1). This laser has previously been investigated, generating ps/fs pulses[2,7,8,9]. Unlike these previous configurations, however, we implement the gain with two sections of dissimilar Er-doped fibres, which are independently pumped, enabling the operating wavelength of the laser to be adjusted simply by varying the pump power. The two gain sections consist of 0.4 m of Er^{3+}-doped fibre (Er concentration 800 ppm), pumped at a constant 150 mW by a 980 nm Ti:Sapphire laser, and 0.9 m of Er^{3+}/Yb^{3+} co-doped fibre (Er concentration 1000 ppm, Yb/Er concentration ratio 12:1), pumped by a mini-YAG laser. Two WDMs were used to couple in the pump beams, and 150 m of standard telecom fibre (STF) followed by a polarising isolator (ISO) provide the necessary nonlinearity for mode-locking. Two sets of polarisation controllers (PC1 and PC2) were placed before and after the isolator to set the polarisation state of the fibre to obtain mode-locked operation.

The use of a multi-segmented fibre laser configuration to implement wavelength control has recently been proposed for a simple cw Fabry-Perot laser[10]. The tuning was not truly continuous, however, but varied in steps of 0.5 nm - 1 nm, which was attributed to undesired etalon effects which are difficult to eliminate completely in a standing-wave cavity. A unidirectional ring cavity should also help considerably in reducing such spurious effects.

With PC1 and PC2 appropriately set, the mode-locked laser self-starts at 10 mW of 1064 nm pump power to the co-doped fibre; the lasing threshold was about 5 mW (note however that the other Er fibre is being pumped by the 980 nm beam). With a maximum of 110 mW pump power supplied to the co-doped fibre, the central operating wavelength of the mode-locked laser was at 1545 nm, producing transform-limited pulses of 1.9 ps. When this power was steadily reduced, the lasing wavelength continuously shifted upwards, arriving at 1549 nm for a pump power of 13 mW. Unlike the discrete tuning steps previously reported[6,10], the tuning was observed to be smoothly continuous, and the operating wavelength could be positioned anywhere within the 4 nm range (to within the 0.1 nm resolution of the optical spectrum analyzer used) simply by changing the power of the pump beam, without mechanical adjustments. Fig. 2 shows some typical mode-locked spectra at 3 different wavelengths, and Fig. 3 shows the tuning characteristic of the laser. Although the output power changes with the wavelength, this is largely reflected in a change in the number of pulses in the cavity, since the individual pulse energies of such fibre soliton lasers are determined primarily by the laser cavity parameters. However, the optical pulse width, monitored by an autocorrelator, was observed to decrease by 20% over the tuning range, as shown in Fig. 4, but remains transform-limited as the optical spectrum correspondingly broadens. When the 1064 nm pump power is decreased further from 13 mW, the lasing wavelength changes directly from 1549 nm to 1558.7 nm, yielding 1.5 ps transform-limited pulses before ceasing to lase altogether as the pump power drops to 5 mW.

The wavelength tuning basically arises because both the gain sections re-adjust themselves as the pump powers are varied, coupled with the useful property that the erbium gain spectral profile changes with inversion[11]. The change of the optical pulse width with wavelength indicates that the mode-locking is wavelength-sensitive over just a few nm. This is likely the result of the linear birefringence of the STF in combination with the ISO, producing a linear filtering effect. Assuming typical beat lengths $L_B \sim O(1)$ m for the STF, the free spectral range (FSR) for the birefringent filter is $\Delta\lambda = \lambda L_B/L_{STF} \sim 10$ nm. It is thus not surprising that the pulse width changes by 20% over a 4 nm tuning range. We have also observed that it was possible to tune the lasing wavelength by twice this range for some other positions of PC1 and PC2, but then mode-locking could not be maintained throughout. This filtering effect, possibly the current limitation to our tuning range, should not be fundamental, however, as using low birefringence fibre with $L_B > 10$ m should increase the FSR of the birefringent filter by an order of magnitude, and enable an increase in the tunability to encompass the full erbium gain bandwidth.

In conclusion, we have demonstrated an integrated all-fibre means for adjusting the wavelength in a passively mode-locked fibre laser. The wavelength can be continuously tuned by simply changing the optical pump power, without requiring any mechanical adjustments. This technique should be very attractive towards the eventual realisation of a compact and rugged wavelength-tunable fibre short pulse source.

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Figure Captions

Fig. 1 Experimental configuration of tunable mode-locked fibre laser.

Fig. 2 Optical spectra for various 1064 nm pump powers (a) 110 mW, (b) 25 mW, and (c) 13 mW.

Fig. 3 Tuning characteristic of mode-locked laser. *Left*: Central wavelength of mode-locked spectrum, *right*: Output power.

Fig. 4 Variation of optical pulse width (left) and corresponding FWHM of optical spectrum (right) with operating wavelength. The time-bandwidth product is between 0.30-0.31 for all these cases.

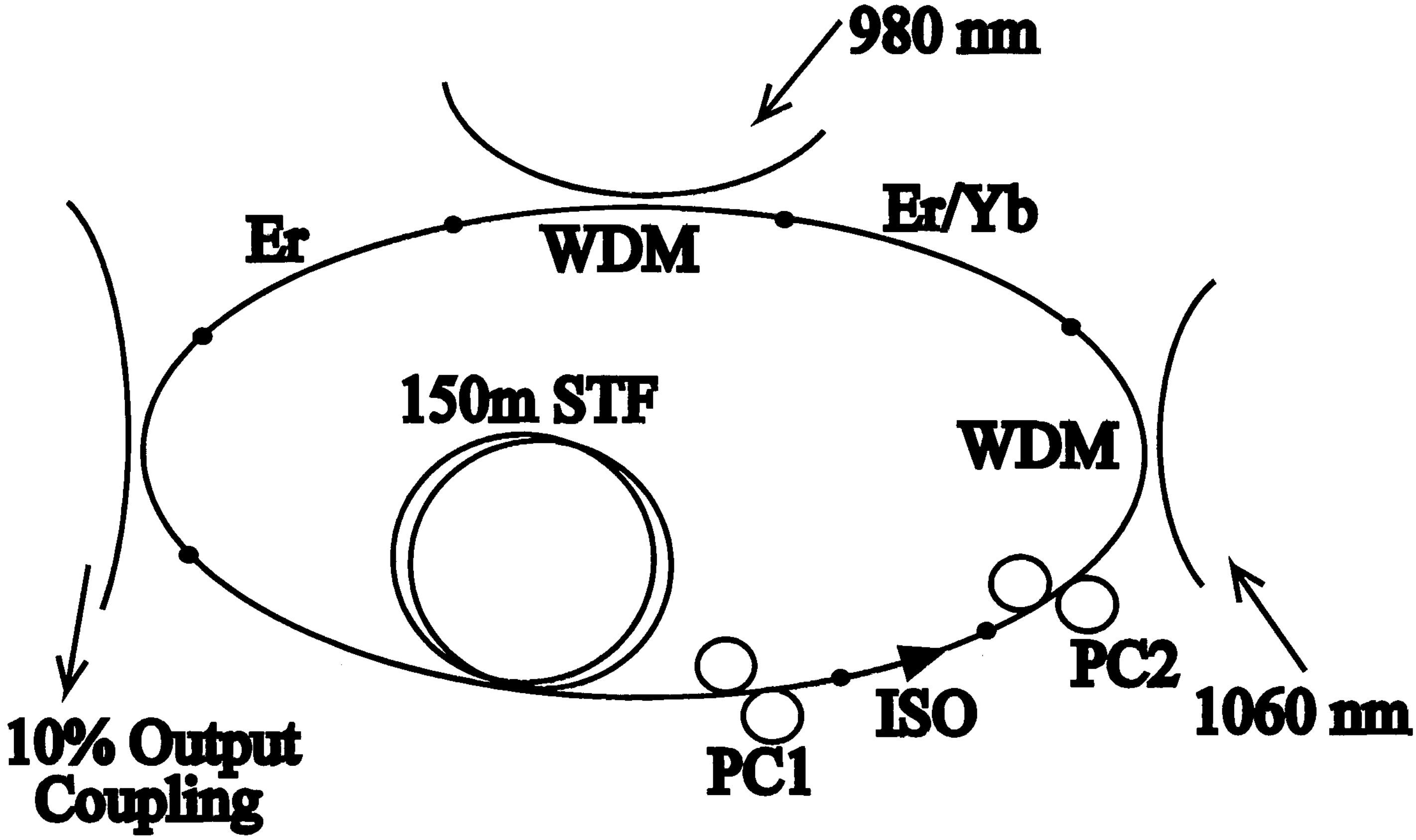

980 nm
Er
WDM
Er/Yb
150m STF
WDM
PC2
ISO
PC1
1060 nm
10% Output Coupling

Fig. 1

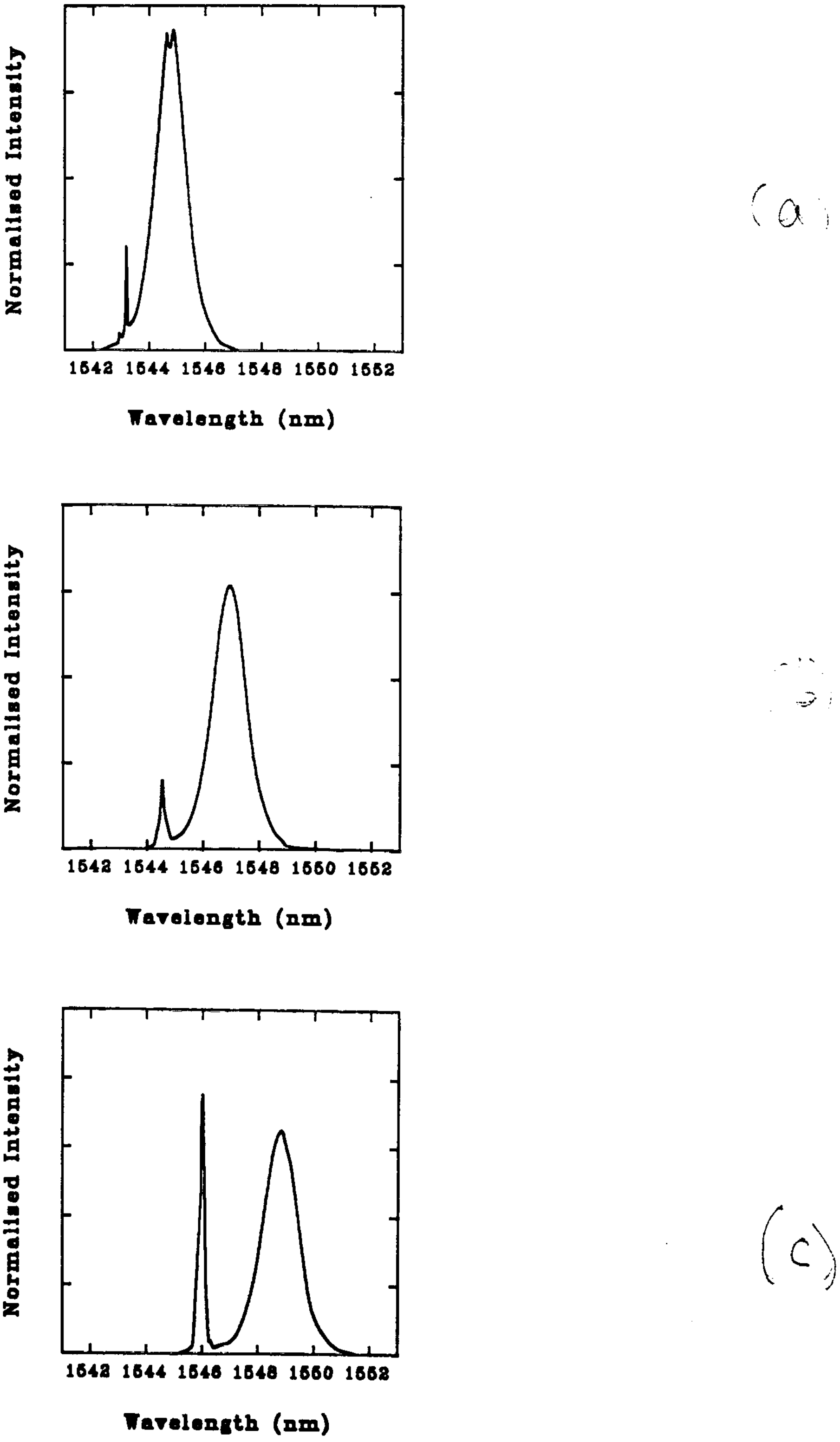

Normalised Intensity
1542
1544
1546
1548
1550
1552
Wavelength (nm)
(a)
(b)
(c)

FIG. 2

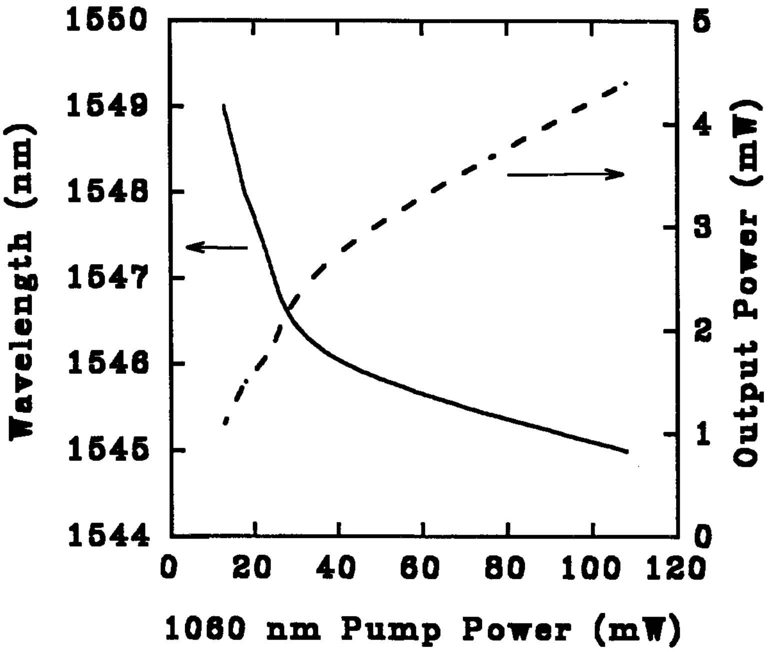
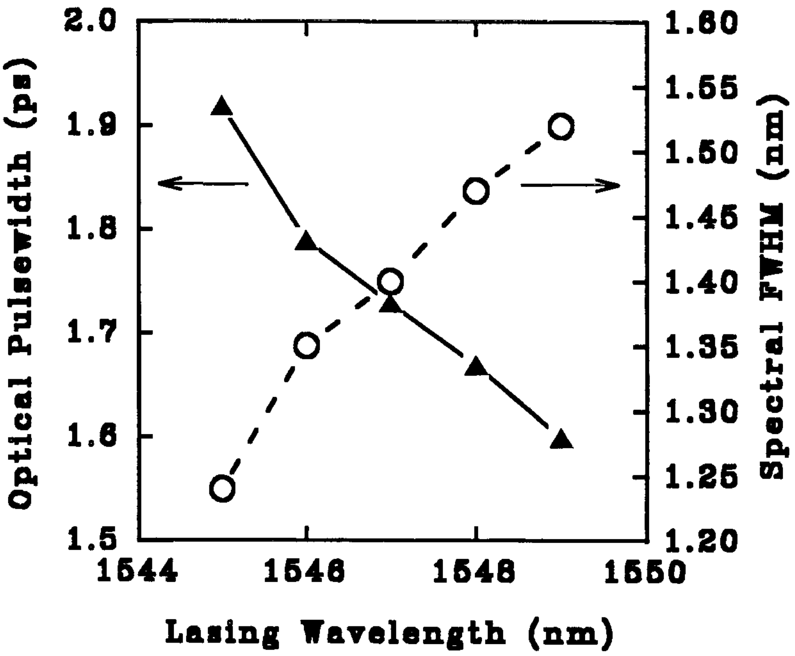

1550
1549
1548
1547
1546
1545
1544
Wavelength (nm)
5
4
3
2
1
0
Output Power (mW)
0
20
40
60
80
100
120
1060 nm Pump Power (mW)

Fig. 3



2.0
1.9
1.8
1.7
1.6
1.5
Optical Pulsewidth (ps)
1.60
1.55
1.50
1.45
1.40
1.35
1.30
1.25
1.20
Spectral FWHM (nm)
1544
1546
1548
1550
Lasing Wavelength (nm)

Fig. 4