493

1373-06

Narrow Linewidth Fibre Laser Sources

Gregory J. Cowle†, Laurence Reekie, Paul R. Morkel, David N. Payne

Optical Fibre Group, Department of Electronics and Computer Science
The University, Southampton, S09 5NH, UK

ABSTRACT

Laser sources based on rare-earth-doped single-mode optical fibres offer considerable potential as narrow-linewidth sources. Fibre laser sources have the capacity to produce highly-coherent, low-noise output, pumped by laser diodes. Fibre lasers are inherently compatible with optical fibres for transmission and sensing applications. Techniques for producing narrow-linewidth and single-longitudinal-mode operation in fibre lasers are reviewed.

2. INTRODUCTION

Fibre lasers are based on well-developed optical fibre technology, modified to include active ions in the form of rare-earth ions in the core of the fibre[1]. Considerable interest has been generated by narrow-linewidth fibre lasers in recent years. Such devices offer the possibility of producing efficient narrow-linewidth or single-longitudinal-mode output, centred at almost any wavelength within the broad fluorescence bandwidth of the rare-earth ions. Fibre lasers have the added advantage of being inherently compatible with optical fibres used as transmission or sensing media.

Several rare-earth dopants have been incorporated into optical fibres to produce fibre lasers. Of particular interest for applications such as sensors and communications are neodymium-doped fibre lasers operating in the 900nm or 1.06μm regions and erbium-doped fibre lasers operating in the third telecommunications window in the 1.5μm region. The interest in narrow-linewidth fibre lasers emanates from the many applications for such lasers. Narrow-linewidth lasers have applications such as in interferometry, metrology and communications. Single-longitudinal-mode lasers operating in the 1.5μm region are important devices for transmitters in single-mode optical communication systems, and will be important for use in future coherent communication systems.

The basic cavity configuration of a fibre laser is to incorporate dielectric mirrors on both ends of a section of rare-earth-doped fibre. The fibre laser is longitudinally pumped through one of the dielectric mirrors by a laser source with a wavelength corresponding to one of the absorption bands of the rare-earth ion. Depending on cavity and pumping conditions, optical linewidths for such fibre lasers may be typically in the range 1 – 15nm. Such broad spectra can occur in a laser with a primarily homogeneously-broadened transition, such as erbium- and neodymium-doped fibre lasers operating at room temperature, because of the broad gain-bandwidth and effect of spatial holeburning on the gain medium. Spatial holeburning is induced by the standing-wave pattern in the laser cavity and can reduce the gain competition between axial modes. This effect, combined with the width of the gain-bandwidth in doped fibre, allows fibre lasers without a wavelength-selective resonator to oscillate over a spectral width equivalent to hundreds or thousands of passive cavity modes.

Fluorescence spectra of the rare-earth ions in a glass host can be very broad. For example, the $^4I_{13/2}$ to $^4I_{15/2}$ transition of $Er^{3+}$is at least 80nm in width[2,3]. This is a necessary property for a tunable laser source based on rare-earth-doped fibre, but means that wavelength-selective laser cavities are required to produce narrow-linewidth operation. The number of modes oscillating in a given laser cavity is determined by the combined effects of spatial holeburning, the gain spectrum of the rare-earth ion and the cavity passive mode-spacing. The passive mode-spacing

---

†On leave from Telecom Australia Research Laboratories, 770 Blackburn Rd, Clayton, Victoria, 3168, Australia

in a laser cavity is determined by the cavity free-spectral-range, which is related to the cavity length L. For the cases of a Fabry-Perot and ring-laser cavities, the passive mode spacing, Δf_{FP} and Δf_R respectively, are given by:

$$\Delta f_{FP} = c/2nL \tag{1}$$

$$\Delta f_R = c/nL \tag{2}$$

where n is the refractive index of the laser medium and c is the speed of light. Typical fibre-laser cavity lengths may be in the order 1 - 10 metres, and hence the cavity mode-spacing and the width of the fluorescence spectra imply that many thousands of modes may oscillate. The cavity and lasing conditions may not be such that every adjacent cavity mode oscillates. Fibre lasers can exhibit lasing spectra with very widely-spaced passive cavity modes oscillating.

Narrow-linewidth operation can be obtained in fibre lasers by incorporating wavelength selectivity into the laser cavity. A wavelength-selective reflector or a filter within the cavity can be used to reduce the bandwidth over which multi-pass gain is possible, resulting in significant spectral narrowing. Alternatively, coupled cavity techniques can be used to introduce periodic loss into the cavity pass-band. Such techniques normally result in spectra with widths typically less than 0.1nm, but still with perhaps tens or hundreds of modes oscillating. Section 3 reviews techniques resulting in such narrow-linewidth operation. Single-longitudinal-mode operation can be achieved in a fibre laser by several methods. One is to design a laser cavity which allows only one cavity mode to fall within the gain-bandwidth of the laser. Such mode-selection techniques are essentially extensions of those used to produce narrow linewidth, but multi-longitudinal-mode fibre lasers. Additionally single-longitudinal-mode behaviour can be achieved by preventing spatial holeburning from occurring. Section 4 reviews these and other techniques for producing single-longitudinal-mode operation in fibre lasers.

The compatibility of fibre lasers with optical fibre technology makes possible the use of devices developed in this technology, such as directional couplers, leading to the possibility of all-fibre narrow-linewidth and single-longitudinal-mode fibre lasers. The criteria for determining the usefulness of a fibre laser source for practical applications would include spectral characteristics, power, efficiency, robustness, size and cost. Many of these aspects have not been considered for the published narrow-linewidth fibre lasers to be reviewed, since they represent early laboratory demonstrations. Many choices, for example that of pump lasers, are often purely for laboratory convenience and could be replaced by more integrated and cheaper alternatives.

3. NARROW LINEWIDTH FIBRE LASERS

Mode-selection techniques can be used to produce narrow-linewidth fibre lasers. These techniques modify the low-loss passband of the laser resonator and thus reduce the number of modes which benefit from multi-pass gain. Techniques for achieving narrow-linewidth operation include grating-reflector fibre lasers, coupled cavity lasers and wavelength-selective fibre ring lasers.

3.1 Grating Reflector Fibre Lasers

One of the simplest methods for producing narrow-linewidth operation in fibre lasers is to use a diffraction grating as a frequency-selective mirror. The first such scheme demonstrated[4] used a bulk diffraction grating in the Littrow configuration as a narrow-bandwidth reflector, as illustrated in Figure 1. Tunable narrow-linewidth operation was demonstrated in this configuration for both Er^{3+}-doped and Nd^{3+}-doped fibre lasers. Figure 2 shows the lasing characteristic of the Er^{3+}-doped version of the laser, produced with an input mirror with 82% reflectivity at 1.54μm. The holographic diffraction grating onto which the fibre output was collimated had 600 lines/mm, blazed at 1.6μm. The active fibre was a 90cm length of Er^{3+}-doped fibre, with cutoff wavelength $\lambda_c = 1\mu m$ and NA = 0.22. Lasing threshold of 30mW absorbed power was observed with a slope efficiency of 0.6%. By rotating the diffraction grating to alter the reflected wavelength, this laser was easily tunable, the tuning range being in two bands of about 14 and 11nm as shown in Figure 3.

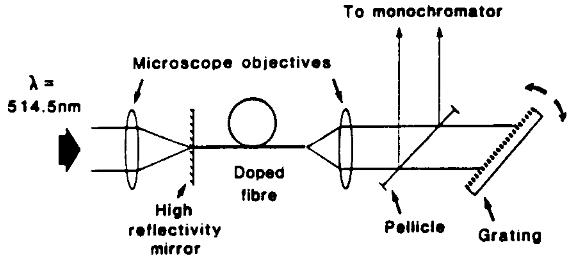

Fig. 1. Schematic description of tunable narrow line fibre laser with Littrow grating reflector[4].

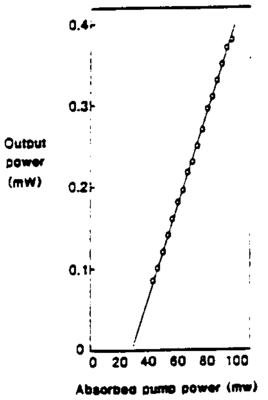

Fig. 2. Lasing characteristic of tunable Er^{3+}-doped fibre laser[4].

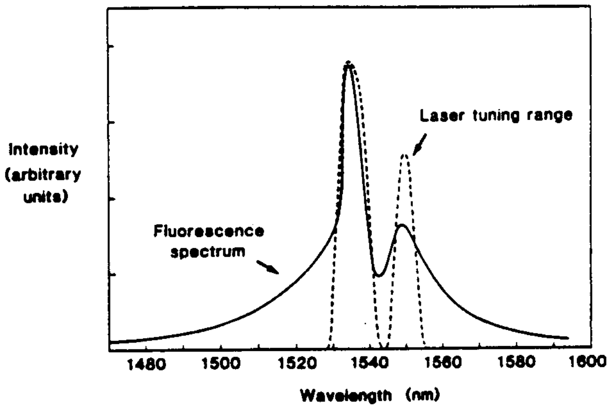

Fig. 3. Tuning range and fluorescence spectrum of Er^{3+}-doped fibre laser with Littrow grating[4].

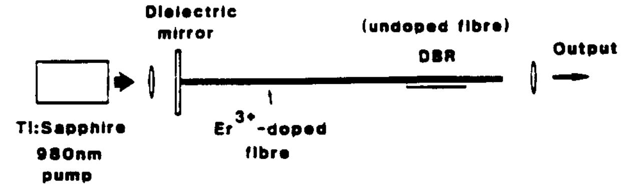

Fig. 4. Schematic of fibre laser with integral DBR.

The use of a grating produces narrow-linewidth operation, the resulting spectral width being determined by the grating pitch, and the approach has the added benefit of being easily tunable over a large fraction of the doped-fibre gain-bandwidth. A disadvantage of the scheme is that it is not integrated and tends to introduce losses, resulting in poor laser slope efficiency.

A more robust, integrated approach to incorporating a frequency-selective grating reflector into a fibre-laser cavity is to use a fibre-distributed-Bragg reflector (DBR). Fibre DBRs formed by producing a diffraction grating in or close to the core of an optical fibre have been shown to be useful devices for producing narrow-band low-loss reflectors[5,6]. These in-fibre reflectors have been fabricated by several techniques, and fall into two general classes. The first class of DBR is fabricated by exposing the core of a single-mode fibre and producing periodic corrugations close to the fibre core. Methods of exposing the core include side-polishing a circular fibre[5] or using a D-fibre[7]. The exposed-field DBR operates by the interaction of the mode evanescent field with the periodic structure. In the second class of DBR a periodic refractive index change is induced in the fibre core by exposure to an interference pattern of ultra-violet light[6].

In each case, to produce first order Bragg reflection in the backward direction, the grating period Λ should satisfy

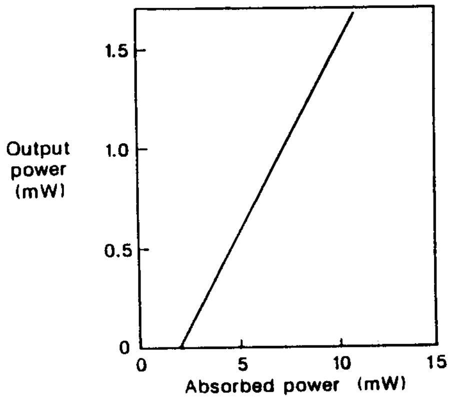

Fig. 5. Lasing characteristic of Nd^{3+}-doped fibre laser with integral DBR[8].

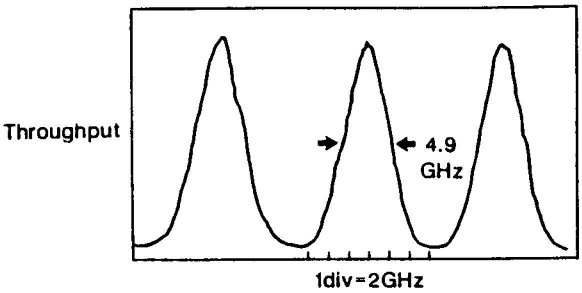

Fig. 6. Spectrum of Er^{3+}-doped fibre DBR laser, measured with Fabry-Perot interferometer[9].

the condition:

$$\Lambda = \frac{\lambda_0}{2n_{eff}} \tag{3}$$

where λ_0 is the free space wavelength of the light and n_{eff} is the effective index of the guided mode. The reflection bandwidth $\Delta\lambda$ follows the approximate relation:

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Lambda}{L} \tag{4}$$

where L is the interaction length of the DBR.

A general schematic for a fibre laser incorporating a DBR is illustrated in Figure 4. The DBR can either be fabricated directly in doped fibre or in undoped fibre which is spliced or butt-joined to a section of undoped fibre. Pump light is introduced through a dichroic mirror which provides the second laser reflector. Operating as a narrow-linewidth laser, the dominant factor determining the laser linewidth is the passive cavity linewidth, which is determined by the DBR linewidth. However, the laser linewidth is typically several orders of magnitude less than the passive cavity width.

Narrow linewidth operation at 1.084μm has been demonstrated[8] in an Nd^{3+}-doped fibre laser using a side-polished, etched DBR, fabricated in undoped fibre with a 3.5μm core and NA = 0.2. Six metres of doped fibre were used, doped with 330ppm Nd^{3+}, and having a 3.5μm core diameter and NA = 0.21. The fibre was butted to the fibre containing the DBR and the laser was diode pumped at 830nm through a high-reflectivity (99%) dichroic mirror. The lasing characteristic shown in Figure 5 illustrates a lasing threshold of 1.9mW (absorbed power) and a slope efficiency of 19%. The spectral characteristics of the narrow-linewidth laser were determined with a Fourier-transform Michelson interferometer. The spectrum had an approximately Gaussian profile with full width at half maximum (FWHM) linewidth of 16GHz (0.6Å).

A similar laser has been demonstrated operating at 1.55μm with Er^{3+}-doped fibre as the active medium[9]. DBR fabrication in this case was identical to that used in the preceding laser, except for the grating pitch. The 2m doped fibre used had a NA of 0.22 and core diameter of 7μm, and was butted to an undoped fibre (NA = 0.12, core diameter 9μm) containing the DBR. The laser was pumped at 650nm from an Argon-ion-pumped CW DCM dye laser. A lasing threshold of 13mW (absorbed power) was obtained with 5% slope efficiency. The laser spectrum as observed on a scanning Fabry-Perot interferometer with Free Spectral Range (FSR) of 13.8GHz and finesse >100 is shown in Figure 6. The spectrum was approximately Gaussian in profile with FWHM of 4.9GHz (0.04nm)

The above two lasers used DBRs fabricated in side-polished fibres, with effective interaction lengths less than 1mm.

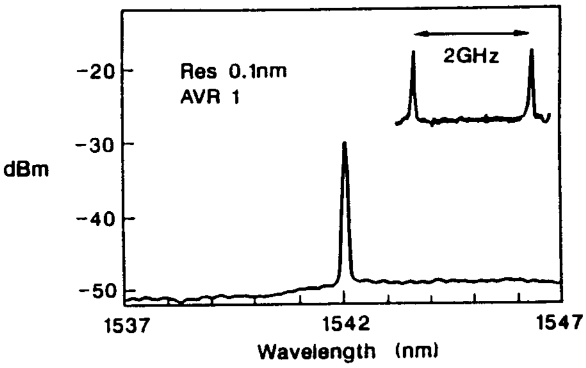

Fig. 7. Spectrum of Er^{3+}-doped fibre laser with D-fibre DBR[7].

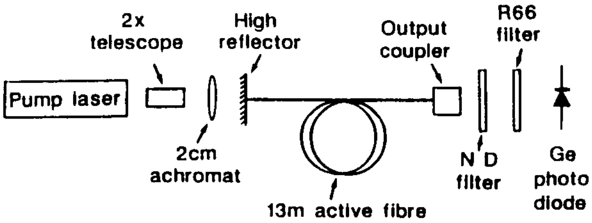

Fig. 8. Block diagram of fibre laser with air-spaced etalon[10].

Using a D-fibre an effective interaction length of 7.5mm has been demonstrated for a DBR[7]. In this case a metallised grating was placed on the D-fibre. Using this DBR as one of the laser-cavity reflectors, an Er^{3+}-doped fibre laser was made using a doped fibre with 0.07-wt.% $Er^{3+}$and $\lambda_c = 1.1\mu m$. The laser was pumped at 514nm from an Argon-ion laser, and the output spectrum is shown in Figure 7. With the very-narrowband reflection achieved from the D-fibre DBR, a linewidth of <20MHz was demonstrated. Limited tunability of 0.6nm (76GHz) was also demonstrated by rotating the bulk diffraction grating, although this method of wavelength tuning does not result in a sturdy device or fast tuning.

The benefit of using integrated grating-reflectors to produce narrow-linewidth fibre lasers is the ability to precisely determine the operating wavelength. On the other hand, bulk gratings in the Littrow configuration allow easy tuning, but have the drawback of being hybrid. While the DBR approach is integrated, it is better suited to producing narrow-linewidth devices with a fixed wavelength, rather than narrow-linewidth tunable devices.

3.2 Coupled Cavity Fibre Lasers

A number of approaches to producing narrow-linewidth operation in fibre lasers have been demonstrated with coupled cavity lasers. These include the incorporation of etalons into cavities and the use of Fox-Smith resonators.

High-power, narrow-linewidth operation has been demonstrated in an Er^{3+}-doped fibre laser by including an etalon within the cavity[10]. An air-spaced etalon was formed between a flat fibre end and a dielectric mirror used as the output coupler, as shown in the schematic of Figure 8. The use of an etalon, as with other interferometric schemes, induces a sharp resonance in the cavity pass-band at discrete optical frequencies. In a laser cavity the etalon acts as a narrowband optical filter. If the periodicity of the filter response is greater than the laser gain-bandwidth, operation on one transmission cycle is possible. Altering the intra-cavity etalon FSR can tune the laser emission wavelength.

In this intra-cavity etalon laser a 13m length of fibre with Er^{3+}concentration of 35ppm, 0.18 NA and 2.5μm core was used. The laser was pumped with an Argon-ion laser operating at 514nm. For 600mW of pump power, in excess of 55mW output power with 10% slope efficiency was obtained at 1556nm. The spectral width of the laser was determined from a measurement of the laser coherence length. Figure 9 shows the coherence function, obtained from a Michelson interferometer. The measured coherence length was 7.7cm, corresponding to a spectral width of 620MHz (0.05Å).

Increased selectivity has been demonstrated by employing both a rotatable grating and a silica etalon[11]. The laser

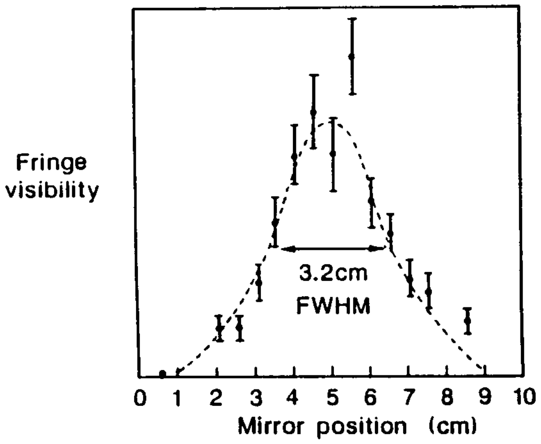

Fig. 9. Coherence function of fibre laser with air etalon. Spectral width = 620MHz[10].

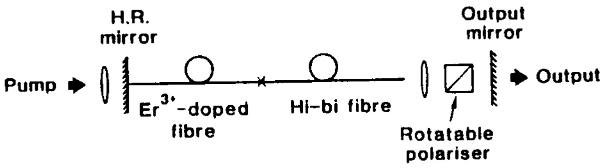

Fig. 10. Schematic of polarimetric Fox-Smith fibre laser.

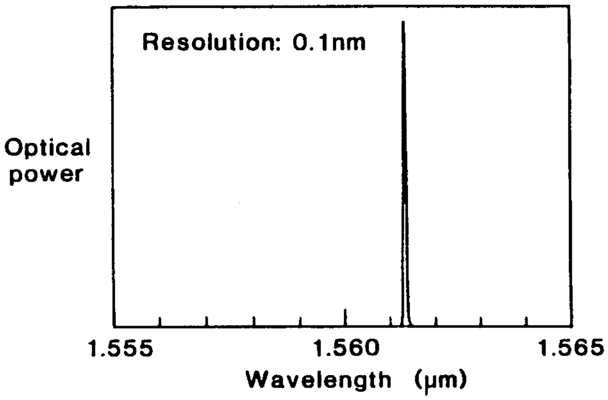

Fig. 11. Monochromator spectrum of polarimetric Fox-Smith fibre laser.

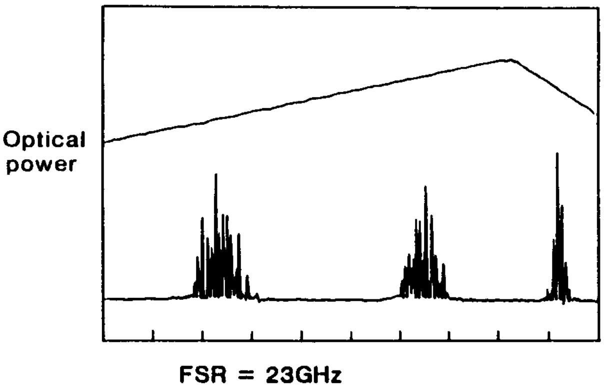

Fig. 12. Fabry-Perot spectrum of polarimetric Fox-Smith fibre laser.

was made with between 5 and 10 metres of doped fibre having an index difference of 0.015, a core diameter of 3μm and an Er^{3+}concentration 1100ppm. Light was coupled onto the grating via a GRIN lens and the fibre was pumped with a Ti:sapphire laser. The spectral width of the fibre laser was 1-2GHz, tunable from 1.52-1.57μm with no etalon, and reduced to 100MHz with the insertion of the etalon. This laser exhibited peak slope efficiency of 51%, with internal quantum efficiency 93-96%.

A novel type of coupled cavity fibre laser configuration which produces narrow linewidth operation is a Fox-Smith cavity operating by the interaction of orthogonally polarised modes[12]. The fibre laser schematically shown in Figure 10 was designed to produce narrow linewidth, single polarisation output. The laser cavity is an interferometric cavity which utilises the birefringence of a high-birefringence single mode fibre to produce a cavity for which the two polarisations have different optical path lengths. The two polarisations are mixed to produce a interferometric cavity by a polariser within the cavity aligned at 45° to the polarisation axes of the high-birefringence fibre. The doped fibre used in the experiment had an Er^{3+}concentration of 800ppm, while the undoped fibre had a beat length of 2mm. By aligning the polariser at 45° to the birefringent axes, narrow-linewidth operation was achieved. Figure 11 shows the laser spectrum observed with a monochromator, while Figure 12 shows the fine structure observable with a Fabry-Perot interferometer.

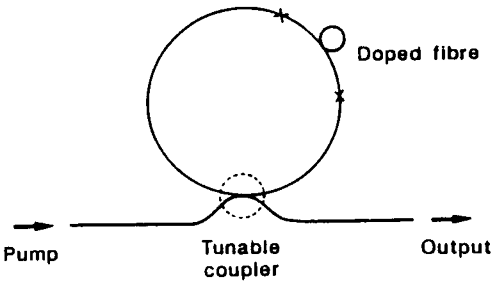

Fig. 13. Schematic of fibre ring laser

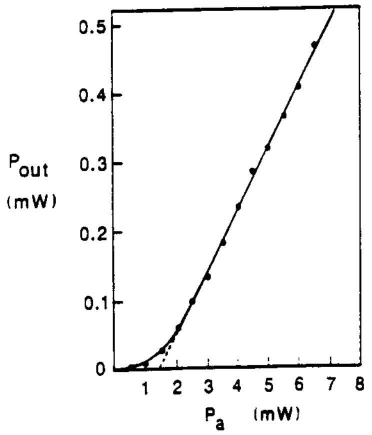

Fig. 14. Lasing characteristic of Nd^{3+}-doped fibre ring laser[13].

In summary, coupled cavity fibre laser cavities have been demonstrated to be useful for producing narrow-linewidth operation, utilising the strong wavelength selectivity of such cavities as intra-cavity filters. Etalons can be useful for producing tunable operation, but necessitate bulk components or air gaps within the laser cavity. The polarametric approach can be made in an all-fibre configuration using a fibre polariser, and thus would be robust and efficient.

3.3 Narrow Linewidth Fibre Ring Lasers

Fibre ring-lasers constructed with wavelength-sensitive single-mode fibre couplers are a convenient route to narrow-linewidth all-fibre lasers. Polished couplers used to create the fibre ring have inherent wavelength sensitivity and act as an all-fibre filter. The ring laser is constructed by joining an input and an output arm of a single-mode fibre coupler to form a circular path incorporating the active fibre. The coupling coefficient of the coupler determines the finesse of the resulting ring resonator. Ring lasers have been demonstrated with narrow linewidth output with both $Nd^{3+}$and Er^{3+}-doped fibres. A schematic for a fibre ring laser is shown in Figure 13. The resonator consists of a polished fibre coupler fabricated in un-doped fibre, with a length of doped fibre completing the ring. Mechanical adjustment of the polished coupler enables the maximum coupling wavelength and maximum feedback wavelength to be tuned.

A fibre ring laser utilising Nd^{3+}-doped fibre has been demonstrated[13] to yield narrow linewidth operation, with the characteristic shown in Figure. The laser had a low threshold of 1-2mW when pumped at 514nm from an Argon-ion laser. Maximum output power of 0.5mW in the clockwise direction was measured for 8mW pump power. Narrow linewidth operation was observed, tunable over a wavelength range of 60nm by adjusting the fibre coupler.

A similar configuration has been demonstrated using Er^{3+}-doped fibre[14]. The doped fibre was characterised by an Er^{3+}concentration of 150ppm, an NA of 0.12 and a core radius of 8μm. The laser was pumped at 532nm from a frequency-doubled Nd:YAG laser and exhibited a lasing threshold of 10mW, with a slope efficiency in the clockwise direction of 6%. The laser spectrum, illustrated in Figure 15 for several pump powers, is less than 0.1nm in width, limited in the measurement by the spectrum analyser resolution. Wavelength variation was possible by varying the coupler characteristic, and the laser exhibited operation at 1532nm, 1555-1575nm and 1590-1603nm.

The ring-laser cavity yields stable, narrow-linewidth operation with limited tunability in an all-fibre device. The achievable linewidth in this technique is determined by the wavelength characteristics of the fibre coupler, and may not be as narrow as other techniques such as fibre DBR lasers. The all-fibre structure of the fibre ring-laser is attractive for its simplicity and low excess loss.

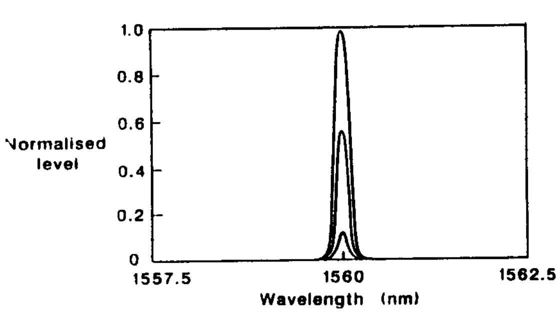

Fig. 15. Laser spectrum of Er^{3+}-doped tunable fibre ring laser[14].

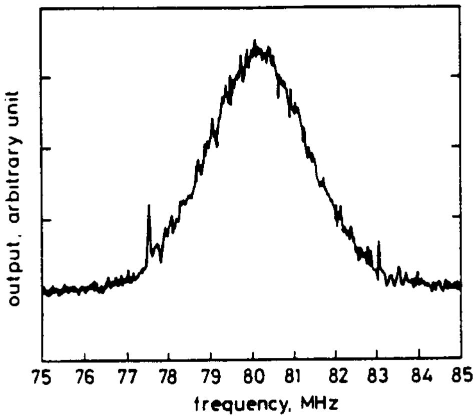

Fig. 16. Spectrum of single longitudinal mode DBR fibre laser (self-heterodyne measurement)[17].

3.4 Other Techniques

Several other techniques have been demonstrated for achieving tunable, narrow-linewidth fibre lasers. In one case mechanical tuning was achieved in an Nd^{3+}-doped fibre laser containing a birefringent filter[15]. The linewidth was measured to be 0.1nm and tuning was achieved by changing the orientation of the birefringent filters. An electronically-tuned Er^{3+}-doped fibre laser was demonstrated which used an intra-cavity acousto-optic modulator (AOM) as the wavelength selective element[16]. The wavelength dependence of the AOM deflection was used as an electronically tunable filter.

4. SINGLE LONGITUDINAL-MODE FIBRE LASERS

Single longitudinal-mode fibre lasers can be produced by several techniques. Some techniques are extensions of mode-selection techniques used to produce narrow-linewidth fibre lasers, taken to the limit where only one cavity mode falls within the gain bandwidth of the doped fibre. Other techniques which have been demonstrated include a travelling-wave ring-resonator and injection-locking of a fibre laser by a narrow-linewidth laser diode.

4.1 Single Longitudinal-Mode Fibre Lasers by Mode Selection

The first demonstration of single longitudinal-mode operation in a fibre laser was in a Nd^{3+}-doped fibre laser with an integral DBR[17]. This technique is simply an extension of a previously-described technique used to demonstrate narrow-linewidth operation, taken to the limit in which only one mode is selected. Because of the broad gain bandwidths available in rare-earth-doped fibre lasers and because typical cavity lengths are long, resulting in close longitudinal-mode spacing, substantial wavelength discrimination is required to achieve single longitudinal-mode operation. The major difference in the determination of spectral characteristics between the single longitudinal-mode version and the narrow-linewidth version is that the single longitudinal-mode version operates such that the linewidth is no longer determined by the reflection bandwidth of the DBR, but rather by parameters such as the laser power, mirror reflectivities, cavity length, and so on, as given by the Schawlow-Townes formula[18]. However, in reality single longitudinal-mode fibre-laser linewidths have not been demonstrated to approach the theoretical Schawlow-Townes limit, but are dominated by other factors such as changes in cavity length due to thermal effects and vibrations.

The fibre used to demonstrate single longitudinal-mode operation in a Fabry-Perot cavity with a fibre DBR had a Nd^{3+}concentration of 0.1%, 0.2 NA and λ_c = 940nm. The DBR was fabricated in the doped fibre and had peak

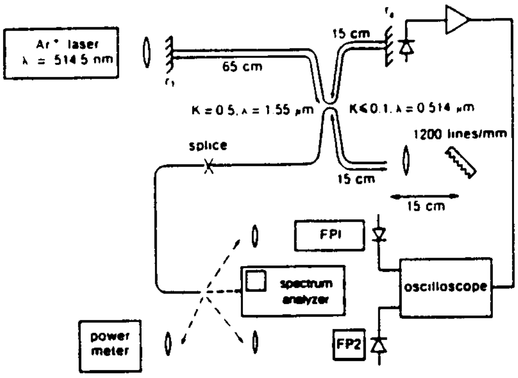

Fig. 17. Er^{3+}-doped Fox-Smith fibre laser[19].

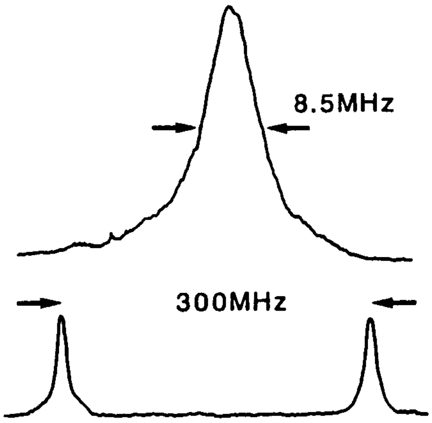

Fig. 18. Spectrum of Er^{3+}-doped Fox-Smith fibre laser, from Fabry-Perot interferometer[19].

reflection at 1082nm with FWHM of 0.8nm. To achieve single longitudinal-mode operation, the fibre length was cut back to a length of 51mm, at which point only one longitudinal mode oscillated. The laser was pumped at 594nm from a CW Rh6G dye laser and exhibited a threshold power of 6mW, with slope efficiency 2.3%. The laser spectrum, measured with a delayed self-heterodyne interferometer, is illustrated in Figure 16. The spectrum consisted of a single mode, having an approximately Lorentzian profile with FWHM of 1.3MHz.

Another mode-selection technique for producing single longitudinal-mode oscillation uses an optical fibre Fox-Smith resonator[19], in this case operating in the 1.5μm region. The Fox-Smith cavity is a coupled cavity and the only modes to oscillate are those which satisfy both cavity conditions. The modes are thus more widely spaced than an equivalent length Fabry-Perot cavity as a result of this Vernier effect. The laser configuration is illustrated in Figure 17. A fused, tapered-coupler was fabricated from Er^{3+}-doped fibre with Er^{3+}concentration 300ppm and $\lambda_c = 1.0\mu m$, and a Fox-Smith cavity formed with path length ratios $L_2/L_1 = 1.13 \pm 0.02$. This cavity, although providing periodic loss, did not provide sufficient discrimination to achieve lasing on one pass-band of the Fox-Smith cavity, so a diffraction grating in the Littrow configuration was used as one of the reflectors. The fibre laser was pumped at 514.5nm from an Argon-ion laser and attained a threshold of 175mW and a slope efficiency of 0.04%. Single longitudinal-mode operation was observed at 1.556μm and the spectrum measured on a scanning Fabry-Perot interferometer is illustrated in Figure 18. The spectral width was measured to be less than 8.5MHz.

Taken to the limit, mode-selection techniques have been demonstrated to be capable of achieving single longitudinal-mode operation. However the width of the gain bandwidths of the rare-earth ions require that substantial wavelength discrimination is necessary in these techniques. That is, high-finesse cavities with large free spectral range are required.

4.2 Travelling Wave Fibre Ring Laser

Techniques other than mode selection have also resulted in single longitudinal-mode operation in Er^{3+}-doped fibre lasers. As described in the introduction, spatial holeburning induced by the effect of the standing-wave pattern on the gain medium is the major reason why fibre lasers oscillate as multi-longitudinal mode rather than single longitudinal-mode devices. Eliminating the standing-wave pattern, and thus the cause of spatial holeburning, by uni-directional operation of a fibre ring-laser has been shown to enable single longitudinal-mode operation[20]. The laser configuration is shown in Figure 19. A dichrioc coupler made in un-doped fibre was spliced to a 1m length of Er^{3+}-doped fibre with an Er^{3+}concentration of 800ppm, $\lambda_c = 1250nm$ and an NA of 0.15. A pigtailed, polarisation-independent isolator was spliced into the loop to introduce differential loss between the clockwise and counter-clockwise directions, and a loop polarisation-controller used to compensate for the slight polarisation anisotropy in the ring. The ring was

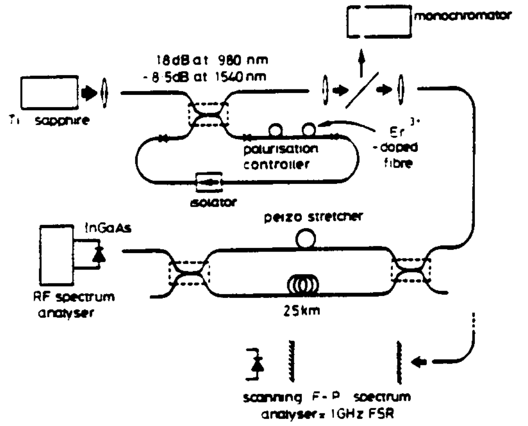

Fig. 19. Travelling wave fibre ring laser experimental configuration[20].

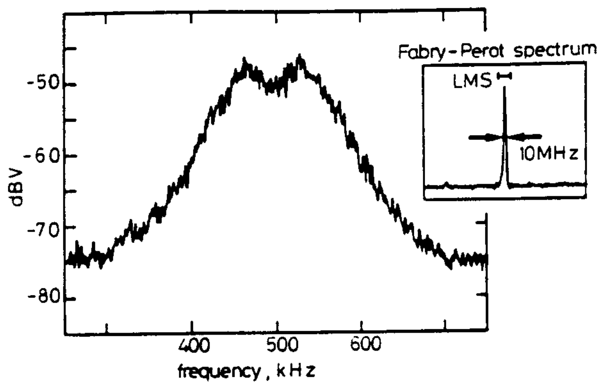

Fig. 20. Self-heterodyne measurement of ring laser spectrum (inset Fabry-Perot spectrum)[20].

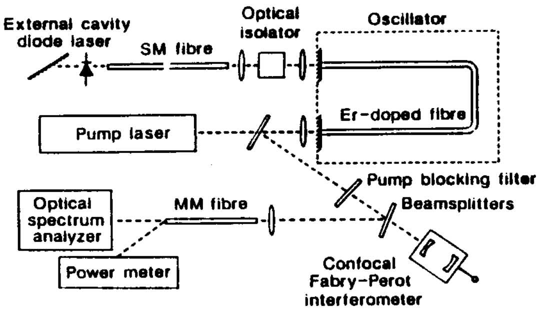

Fig. 21. Experimental arrangement of injection locked fibre laser[21].

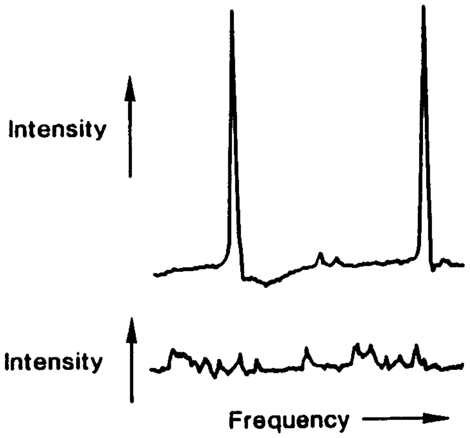

Fig. 22. Fabry-Perot trace of injection locked fibre laser with(u) and without(l) injected signal[21].

pumped at 980nm from a Ti:sapphire laser and achieved a threshold of 6mW and 2.3% slope efficiency. Adjusting the loop polarisation controller enabled single longitudinal-mode operation at $1.555\mu m$. The spectrum measured with a scanning Fabry-Perot interferometer is shown in Figure 20, illustrating that the spectral width was less than 60kHz FWHM.

4.3 Injection-Locked Fibre Laser

Another approach to obtaining single longitudinal-mode output from a fibre laser is to injection-lock the fibre laser. This technique has recently been demonstrated[21] using the arrangement illustrated in Figure 21. An erbium fibre laser pumped by an Argon-ion laser operating on the 528nm line was injection locked by an external cavity semiconductor diode laser. The fibre laser consisted of a 2.5m length of fibre with an Er^{3+}concentration of 500ppm, a core diameter of $3\mu m$ and $\lambda_c = 1.15\mu m$. With no injected signal the fibre laser exhibited multi-longitudinal mode behaviour, but with an injected signal close in frequency to the free-running fibre laser frequency, single longitudinal-mode oscillation was observed, as indicated from the Fabry-Perot spectrum shown in Figure 22. This laser was observed to be sensitive to changes in optical path length due to physical expansion and temperature effects. Active stabilisation would be required because of the stringent stability requirements.

5. SUMMARY

Narrow-linewidth operation in fibre lasers has been demonstrated by several techniques, including lasers with grating-reflectors, ring-lasers and coupled cavity lasers. Perhaps the best techniques in terms of stability and robustness are fibre lasers incorporating fibre DBRs and fibre ring-lasers. By taking advantage of all fibre components, these lasers maintain the waveguiding nature of the laser cavity, with resulting high efficiency. Sacrificing efficiency, superior tunability is possible, including fast electronic tunability.

Single longitudinal-mode operation is more difficult in fibre lasers, but has been demonstrated using several widely-varying techniques, with resulting linewidths less than 60kHz demonstrated. Such linewidths are still far from the theoretical Schawlow-Townes limit which is around 1Hz. Improvement in linewidths should be possible, but ultimately temperature and mechanical stability will determine the limit.

Most devices demonstrated to date are experimental laboratory lasers, many giving poor performance due to their non-integrated construction. High efficiency and good performance are possible in fibre lasers[22], and fully engineered, high performance diode-pumped versions of most devices described should be possible.

Low-threshold, narrow-linewidth and single longitudinal-mode fibre lasers have been demonstrated as viable, highly-coherent sources, some configurations also offering tunability over a large wavelength range. Such lasers have potential as sources for communications and sensors.

6. ACKNOWLEDGEMENTS

This work was partially sponsored by the ESPRIT program of the European Community. The authors would like to thank the Association of Commonwealth Universities for providing a student scholarship (GJC).

7. REFERENCES

1. S.B. Poole, D.N. Payne and M.E. Fermann, "Fabrication of Low-Loss Optical Fibres Containing Rare-Earth Ions," *Electron. Lett.*, vol. 21, pp. 737-738, 1985.
2. B.J. Ainslie, S.P. Craig and S.T. Davey, "The Absorption and Fluorescence Spectra of Rare Earth Ions in Silica-Based Monomode Fiber," *J. Lightwave Tech.*, vol. 6, no. 2, pp. 287-293, February 1988.
3. S.B. Poole, D.N. Payne, R.J. Mears, M.E. Fermann and R.I. Laming, "Fabrication and Characterisation of Low-loss Optical Fibers Containing Rare-Earth Ions," *J. Lightwave Tech.*, vol. 4, pp. 870-876, 1986
4. L. Reekie, R.J. Mears, S.B. Poole and D.N. Payne, "Tunable Single-mode Fiber Lasers," *J. Lightwave Tech.*, vol. 4, no. 7, pp. 956-960, July 1986.
5. C.J. Rowe, I. Bennion, and D.J. Reid. "High-Reflectivity Surface-relief Gratings in Single-mode Optical Fibres", *IEE Proceedings*, vol. 134, pt. J, no. 3, pp. 197-202, June 1987.
6. G. Meltz, W.W. Morley and W.H. Glen, "Formation of Bragg Gratings in Optical Fibres by a Transverse Holographic Method", *Opt.Lett.*, vol. 14, no. 15, pp. 823-835, 1989.
7. P. Yennadhiou and S.A. Cassidy, "D-fiber Grating Reflection Filters," *Proc. OFC'90*, paper TUG4, p. 27, January 1990
8. I. M. Jauncey, L. Reekie, R.J. Mears, D.N. Payne, C.J. Rowe, D.C.J. Reid, I. Bennion and C. Edge, "Narrow-linewidth Fibre Laser with Integral Fibre Grating", *Electron. Lett.*, vol. 22, no. 19, pp. 987-988, September 1986.

9. I.M. Jauncey, L. Reekie, R.J. Mears and C.J. Rowe, "Narrow-Linewidth Fiber Laser Operating at 1.55μm," *Opt. Lett.*, vol. 12, pp. 164-165, March 1987.

10. M.S. O'Sullivan, J. Chrostowski, E. Desuvire and J.R. Simpson, "High-Power Narrow-Linewidth Er^{3+}-doped Fiber Laser", *Opt. Lett.*, vol. 14, no. 9, pp. 438-440 May 1989.

11. R. Wyatt, "High-power Broadly Tunable Erbium-doped Silica Fibre Laser", *Electron. Lett.*, vol. 25, no. 22, pp. 1498-1499, October 1989.

12. P.R. Morkel and G.J. Cowle *unpublished results*

13. Y. Chaoyu, P. Jiangde and Z. Bingkun, "Tunable Nd^{3+}-doped Fibre Ring Laser," *Electron. Lett.*, vol. 25, no. 2, pp. 101-102, January 1989.

14. P.L.Scrivener, E.J. Tarbox and P.D. Maton, "Narrow Linewidth Tunable Operation of Er^{3+}-doped Single-Mode Fibre Laser," *Electron. Lett.*, vol. 25, no. 8, pp. 549-550, April 1989.

15. I.P. Alcock, A.I. Ferguson, D.C. Hanna and A.C. Tropper, "Tunable, Continuous-wave Neodymium Doped Monomode Fibre Laser Operating at 0.900 - 0.945μm and 1.070 - 1.135μm," *Opt. Lett.*, vol 11, pp. 709 - 711, Nov. 1986.

16. P.F. Wysocki, M.J.F. Digonnet and B.Y. Kim, "Electronically Tunable, 1.55μm Erbium-doped Fiber Laser," *Opt. Lett.*, vol. 15, no. 5, pp. 273-275, March 1990.

17. I. M. Jauncey, L. Reekie, J.E. Townsend, D.N. Payne and C.J. Rowe, "Single-longitudinal-mode Operation of an Nd^{3+}-doped Fibre Laser," *Electron. Lett.*, vol. 24, no. 1, pp. 24-26, January 1988.

18. O. Svelto, *Principles of Lasers*, Plenum Press, New York, 1982.

19. P. Barnsley, P. Urquhart, C. Millar and M. Brierley, "Fiber Fox-Smith Resonators: Application to Single-Longitudinal-Mode Operation of Fiber Lasers," *J. Opt. Soc. Am. A*, vol. 5, no. 8, pp. 1339-1346, August 1988.

20. P.R. Morkel, G.J. Cowle and D.N. Payne, "Travelling-Wave Erbium Fibre Ring Laser With 60kHz Linewidth," *Electron. Lett.*, vol. 26, no 10, pp. 632-634, May 1990.

21. J.D.C. Jones and P. Urquhart, "An Injection-locked Erbium Fibre Laser," *Opt. Comms*, vol. 76, no. 1, pp. 42-46, April 1990.

22. M. Shimitsu, H. Suda and M. Horiguchi, "High-efficiency Nd^{3+}-doped Fibre Lasers Using Direct-coated Dielectric Mirrors," *Electron. Lett.*, vol. 23, pp. 768-769, 1987.