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CHAPTER VI

NARROW-LINEWIDTH AND TUNABLE FIBER LASERS

P.R.Morkel

University of Southampton, U.K.

CONTENTS

1. Introduction

Fiber laser devices based on rare-earth ions incorporated into various glass types have generated considerable interest as narrow linewidth sources, and a number of research groups have published results in this area. Inherent compatibility with optical fiber transmission and sensing media are an obvious attraction for the use of fiber laser devices as sources in fiber communication and sensor applications where narrow linewidths are required. In particular, potential future coherent optical communication systems using wavelength division multiplexing (WDM) will require tunable, narrow-line laser sources. The broad lineshapes associated with rare-earth-doped glass media allow tunable fiber laser sources to be fabricated. The strong optical confinement associated with single-mode fiber laser media enables substantial gain to be obtained over a large fraction of the total emission lines, for both 3-level and 4-level transitions, and hence broad tunability is possible. The potential exists therefore for tunable, narrow linewidth and single longitudinal-mode fiber sources which could find wide application in the field of optical fiber communications and sensors. The ability to convert emission from laser diode pump sources which can be of low modal and temporal quality into highly coherent, low-noise laser emission is an attractive feature of rare-earth lasers in general.

The ultimate aim of the development of narrow linewidth fiber laser devices is to provide rugged and stable narrow linewidth or single frequency sources, pumped by a semiconductor laser diode with the capacity of rapidly electronic tunability. Also at low cost! A challenging target certainly, although as will be seen in this chapter, all of the above requirements have been addressed to some extent in various fiber laser devices developed to date. The cost issue has yet to be addressed, although the relative ease of fabrication of bulk quantities of fiber laser gain media (see chapter I: Fiber fabrication), along with expected high yields in device fabrication indicate that low cost devices can be expected. A single device offering all of the above characteristics has yet to be developed although considering the relative youth of modern single-mode fiber laser technology, progress in this field to date has been substantial.

In this chapter the published techniques for constructing narrow linewidth, tunable and single frequency fiber laser sources are reviewed. The primary rare-earth materials which have been studied in this context are neodymium and erbium doped fibres operating in the 900nm, 1.06μm and 1.5μm regimes, and these will be treated here. Longer wavelength tunable devices fabricated from Tm^{3+}-doped fibers have also been demonstrated using similar techniques to those described in this chapter, and these will be treated in a separate chapter (see chapter IX). The operation of erbium doped fibres around 1.55μm in particular is of great interest as a possible source for future telecommunication systems operating in the region of minimum loss in silica fibers.

In general for a laser medium subject primarily to homogeneous gain saturation, i.e. without significant spectral hole burning, such as Nd^{3+} and Er^{3+} doped fibers operating at room temperature (see chapter II), a major cause of spectral broadening is the effect of spatial hole burning. The effect of spatial hole burning is to favour oscillation on a number of cavity modes, often widely spaced in frequency. The additional gain available for widely spaced modes will usually be small however, and weakly wavelength selective feedback can often be used to ensure narrow line operation. A number of wavelength selective elements have been used to enable line narrowing of the emission of fiber laser devices including fiber devices, bulk and acousto-optic components. In addition, removal of spatial hole burning by, for example, operating a fiber laser in a travelling wave mode can be effective in ensuring narrow line operation and this approach is treated in this chapter. The various approaches taken to date to ensure narrow line operation will all be reviewed and the tunability assessed in various cases. Approaches which have enabled single longitudinal-mode operation will be reviewed and the future for such devices discussed.

2. Line narrowed fiber laser devices

Fiber laser structures fabricated without wavelength selectivity typically oscillate with optical linewidths in the range 1-15nm depending on various parameters such as cavity loss and pump power (see chapter VII). These spectral widths typically encompass thousands or tens of thousands of passive cavity modes.

In this section fiber laser devices which have been shown to give narrow linewidth but multi-longitudinal-mode non-tunable emission will reviewed. This will be termed single-wavelength line narrowed operation in contrast to tunable line-narrowed operation which will be treated in the next section. In the context of this chapter, narrow-linewidth or line-narrowed operation is defined as that giving an output of < 1nm spectral width, this type of operation requiring some form of wavelength discrimination. In most cases of the narrow-linewidth devices described in this chapter, the actual measured linewidth, which is determined primarily by the wavelength discrimination of the cavity is < 0.1nm, corresponding to tens or hundreds of modes. Two techniques have been used to generate single-wavelength, line-narrowed emission from fiber lasers, based on the use of fiber gratings and intra-cavity etalons. Both techniques will be discussed here.

Integral fiber reflective Bragg grating lasers

Fiber gratings or distributed Bragg reflectors formed by etching periodic structures very close to a fibre core have been shown to give narrow linewidth reflectivity, with the center wavelength of the reflection determined by the grating period and the linewidth determined by the grating length[1]. Fabrication of a grating with suitable period can produce narrow-band reflectivity within the spectrum of emission of a fiber laser which can be used as one of the cavity feedback elements. Fig.1 shows the reflection characteristic of a grating formed for use with a Nd^{3+}-doped germano-silica fibre[2] which has a peak emission wavelength of 1.088μm. In this case the peak reflectivity wavelength was 1.084μm. Gratings with appropriate pitch have effectively been employed to narrow the spectrum of emission of Nd^{3+} and Er^{3+} -doped silica fiber lasers[2,3,4]. Fig. 2 shows a general schematic of the laser configuration used[2]. Pump light is coupled into the doped fiber through a dichroic dielectric mirror using conventional optics. The fiber grating is incorporated onto the other fiber end and provides narrow-band feedback. Emission of light centred at 1.084μm with 16GHz spectral width has been obtained for the neodymium system. Fig. 3 shows a laser input/output characteristic for the Nd^{3+} laser, pumped at 830nm with light from a laser diode source. As can be seen, in excess of 1.5mW of narrow band light was obtained.

For the case of narrow-line Er^{3+}-doped fiber lasers, polished fiber[3] and modular D-fiber grating reflection filters[4] have been used in similar configurations to the Nd^{3+} narrow line fiber laser described above. The D-fiber grating has the advantage of enabling longer grating interaction lengths than polished devices to be achieved, resulting in narrower spectral response. In this case, the D-fiber grating had a 13GHz bandwidth, approximately one order of magnitude less than that of the polished fiber grating (130GHz). In each case the reflection bandwidth was measured with incoherent light. For the polished fiber grating laser, an emission linewidth of 4.9GHz at 1.551μm was obtained by pumping a 2m length of fiber with light at 650nm from a DCM dye laser. Fig. 4 shows the laser characteristic indicating a threshold of $\approx$10mW with a slope efficiency of $\approx$4.6%. Using the longer D-fiber grating filter with a 7m length of Er^{3+}-doped alumino-silicate fiber pumped at 514nm, the emission was at 1.542μm and the spectral width measured to be <20MHz. Fig. 5 shows the spectral emission obtained for this fiber laser. A small degree of wavelength tuning of 0.6nm was obtained by mechanically rotating the grating. Note that the linewidths of the fiber lasers incorporating grating reflectors are significantly narrower than the 3dB bandwidth of the grating reflector itself.

More recently a photorefractive reflection grating, written into the core of a germano-silicate fiber by transverse illumination with light at 257.3nm, has been used to generate single-wavelength line-narrowed emission from an Er^{3+}-doped fiber laser[5]. Such fiber reflection gratings have the advantage of low insertion loss and low polarisation sensitivity (see chapter III: Devices for fiber lasers). The grating used in this work had a reflectivity of 0.5% at 1.538μm with a 3dB reflectivity bandwidth around 1nm. Gratings with reflectivities an order of magnitude higher than this value can also readily be fabricated.

The laser cavity incorporating the photorefractive grating consisted of a 30m length of Er^{3+}-doped fiber with a dielectric HR @ 1.55μm mirror providing feedback at one end of the cavity and the fiber-grating butted to the other end of the fiber. Pumping through the dielectric mirror with light at 980nm from at Ti:Al_2O_3 laser enabled laser oscillation at a wavelength of 1537.5nm corresponding to the peak reflectivity wavelength of the fiber grating. A laser threshold of 40mW launched pump power and slope efficiency of 54% were obtained. The time averaged linewidth was measured to be $\approx$1GHz.

Intra-cavity etalon laser

Intra-cavity etalons are conventionally used in a number of laser types to reduce the bandwidth of oscillation. Inclusion of an etalon has the effect of inducing a periodic cavity loss characteristic, determined by the finesse and optical length of the etalon, which can be used to favour emission over a narrow band. Ensuring that the periodicity induced by the etalon is greater than the gain bandwidth of the laser enables the laser to operate within a single cycle of the transmission characteristic and hence line-narrowing of the laser can be effected. In general a small degree of wavelength selectivity, particularly in homogeneously broadened systems, can be used to narrow the emission line. A high-power narrow-linewidth Er^{3+} fiber laser has been demonstrated[6], which operates in a narrow line by virtue of an intra cavity etalon formed between a bare fiber end and an output coupler dielectric mirror. In this case a 13m length of germano-silicate fiber doped with 35ppm Er^{3+} was used, pumped at 514nm with light from an Ar^{2+} laser. In excess of 55mW of output power at 1566nm was obtained for around 600mW of pump power at room temperature. Fig. 6 shows the experimental configuration and Fig. 7 shows the laser input/output characteristic, with data taken both at room temperature and liquid nitrogen temperature (77K). The spectral width of the laser output was inferred from a measurement of the coherence length. Using a Michelson interferometer a coherence length of 7.7cm was measured which corresponds to a spectral width of 620MHz, or approximately 0.05Å. Fig. 8 shows the coherence function obtained for this laser.

From the above it can be seen that fiber gratings have been the favoured components used for generating single-wavelength, line-narrowed emission from fiber lasers. Four experiments have been described using fiber gratings, either of etched or photorefractive type, compared with one report of the use of an intra-cavity etalon. In addition all but one of the reports refer to Er^{3+}-doped fiber lasers, reflecting the interest in the 1.55μm wavelength of operation. Er^{3+}-doped fiber lasers using fiber gratings have shown a $<$20MHz linewidth and very high efficiencies when pumped at appropriate wavelengths. Single longitudinal-mode emission has also been obtained with Nd^{3+}-doped fibers in a short cavity configuration and this will be treated in the section describing single frequency fiber lasers. Use of fiber gratings is attractive in that all-fiber structures can be constructed, and in principle, very narrow band reflectivity filters can be fabricated (see chapter III). Generation of gratings within rare-earth-doped germano-silicate fibers themselves will also be possible, enabling a single-component narrow-linewidth fiber laser to be constructed. The intra-cavity etalon approach does have an advantage of providing for tunability however. Variation of the etalon length tunes the wavelength of minimum cavity loss and this may prove to be an attractive means of tuning a fiber laser.

3. Tunable, line narrowed fiber laser devices

In this section a number of fiber laser devices which have given tunable, line narrowed operation are reviewed. A number of approaches have been taken including the use of conventional bulk-optic dispersive elements, as well as the use of novel fiber structures.

Ring lasers using wavelength selective coupler components

Ring lasers constructed with wavelength sensitive polished single-mode couplers have been fabricated with both Nd^{3+} and Er^{3+} doped fibers and show narrow emission spectra. Fig. 9 shows an experimental configuration used to fabricate a Nd^{3+} ring laser out of a single length of Nd^{3+}-doped fiber[6]. A polished coupler was formed with the doped fiber, enabling a 3m long re-entrant, resonant structure to be fabricated. Polished fiber couplers show inherent wavelength sensitivity in the degree of coupling, and this facet of their behaviour was used to induce narrow band feedback in a resonant structure.

Mechanically adjusting the degree of coupling in the polished device enabled the maximum coupling wavelength and hence the maximum feedback wavelength to be tuned.

Pumping the laser structure indicated in Fig. 9 with light at 514nm from an argon-ion laser gave rise to narrow-band emission, with the characteristic indicated in fig. 10. A low threshold of 1-2mW was observed and a maximum output of ≈0.5mW obtained at 8mW of pump power. The output power indicated in Fig. 10 relates to only the clockwise (CW) circulating mode of the ring laser. A counter-clockwise mode of equal power will also exist, the output of which will be directed back along the path of the pump beam and hence in this configuration will be lost. Adjustment of the coupler enabled the emission to be tuned over a wavelength range of 60nm which corresponds to a substantial fraction of the total emission linewidth of the material.

A narrow-line and tunable Er^{3+}-doped fiber laser has also been demonstrated using a re-entrant polished coupler[8]. Fig. 11 gives the configuration of the Er^{3+} fiber laser which was pumped with light at 532nm from a frequency doubled Nd:YAG laser. The configuration is similar to that of Fig. 9 with the exception that in this case the coupler is fabricated from un-doped fiber and a length of doped fiber is spliced between two coupler ports. An advantage of this set-up is that no wasteful absorption of pump light takes place external to the resonator, as is the case when a single length of doped fiber is used. Fig. 12 shows the laser input/output characteristic obtained for the laser operating at 1.56μm. A threshold power of 10mW and uni-directional slope efficiency of 6% were obtained. Fig. 13 shows the spectrum of the laser output at 1.56μm at pump power levels up to four times the threshold level. A resolution limited linewidth of 0.1nm is indicated in each case. Mechanical adjustment of the polished coupler component enabled tuning of the laser in three discrete ranges within a 70nm wavelength region as indicated in Fig. 14. Operation of erbium glass and fiber lasers in discrete wavelength ranges[9,10] has also been observed in cavities without dispersive elements and has been attributed to the substantial Stark splitting of the energy levels, in particular the ground state[10,11]. This causes the wavelength of maximum gain, and hence the preferred wavelength of operation, to vary with pumping and cavity loss conditions.

Tunable lasers using bulk-optic components

a) Mechanical tuning

Fiber lasers have also been tuned by incorporating conventional bulk-optic dispersive components within laser cavities containing fiber amplifier gain media[12,13,14] and mechanically tuning the response of the dispersive component. Fig. 15 shows a schematic cavity configuration for a tunable laser using Nd^{3+}-doped fiber, which was pumped at 590nm with light from an Argon-ion laser pumped dye laser[11]. The fiber used was a germano-silicate type doped with ≈300ppm Nd^{3+} which gives a peak emission wavelength of 1.088μm on the $^4F_{3/2}$-$^4I_{11/2}$ 4-level transition. The fiber laser contained a birefringent filter as the dispersive element and could be operated on the $^4F_{3/2}$-$^4I_{11/2}$ 4-level transition around 1.088μm or the $^4F_{3/2}$-$^4I_{9/2}$ 3-level transition around 900nm. Maximum output powers of 2mW for 35mW of absorbed pump power and 3mW for 53mW of absorbed pump power were obtained for the two respective transitions. The minimum laser threshold powers for the two transitions were 12mW and 8mW. The emission linewidth in each case was measured to be approximately 0.1nm. Fig. 16. shows the tuning curve around 900nm obtained by adjusting the orientation of the birefringent filters. A continuous tunable range of 45nm from 900nm to 945nm was obtained. Fig. 17 shows the tuning characteristic obtained for the 1.06μm transition. In this case continuous tunability of 65nm from 1.070μm to 1.135μm was available. Continuous tuning in this context indicates that laser oscillation can be obtained throughout the tuning range indicated although the actual cavity modes excited will vary across the range.

As well as birefringent filters, dispersive reflection gratings have been used to construct tunable fiber lasers[13,14]. Fig. 18 shows the laser configuration used in reference 13 where the pump wavelength was 514nm from an Argon-ion laser. For a Nd^{3+}-doped fiber laser an emission spectrum of 0.25nm FWHM with a tuning curve as shown in Fig. 19 was obtained. Fig. 20 indicates the laser characteristic with a laser threshold power of 30mW and 1.7% slope efficiency. A similar laser construction using Er^{3+} doped fiber, again pumped at 514nm, gave the tuning range indicated in Fig. 21 and the laser characteristic shown in fig. 22. The laser tuning curve again shows discrete operating wavelength ranges giving an overall 25nm tuning range. From Fig. 22 it can be seen that the threshold power for this laser was approximately 30mW with a 0.6% slope efficiency.

More recently, a grating tuning mechanism has been used to continuously tune an erbium fiber laser over 70nm around 1.55μm[14]. Efficient operation was obtained in this case by pumping the doped fiber with light at 980nm which shows negligible excited state absorption (see chapter II: Spectroscopy of rare-earth-doped fibers). A narrow-linewidth output power in excess of 250mW, tunable over a 50nm range was obtained for an input pump power of 540mW. Fig. 23 indicates the experimental configuration used where a 3.5% Fresnel fiber end reflection was used as the laser output coupler. The other fiber end was butted to a silica plate to reduce the coupling of Fresnel reflection light back into the fiber. At this end feedback was provided by reflection from a rotatable reflection grating. An etalon could also be incorporated between the silica plate and the grating to further line narrow the laser emission. For a high gain system such as Er^{3+}-doped fiber, such a low value of output coupler reflectivity (3.5%) can be used to provide highly efficient operation by minimising the effect of other intra-cavity losses. A minimum threshold of 10mW pump power was observed. The spectral width of the laser output was measured to be 1-2GHz in the free-running case or 100MHz with the incorporation of a 2mm glass etalon within the cavity. Fig. 24 shows the tuning curves obtained for two fiber lengths (5.5m & 9.5m) at an input power of 540mW at 980nm showing continuous tunability over the emission band in contrast to other results obtained with the erbium system. Continuous tunability in this case is a result of the high wavelength discrimination available with the grating filter and the high level of efficient pumping, enabling substantial gain to be obtained over a large proportion of the emission band. For the longer fiber length very high overall efficiency of 50% was obtained which was inferred to indicate 93-96% quantum efficiency in the gain medium. Note also that an essentially flat tuning response over a major part of the tuning curve was observed, a characteristic which may be expected for operation substantially above the threshold pump power level.

b) Electronically tuned fiber laser

Although mechanical tuning of a fiber laser device allows for precise setting of the wavelength of operation over a wide range, for a number of potential applications rapid electronic control of the output wavelength is desirable. Electronic tuning of an erbium doped fiber laser operating around 1.54μm has been achieved with the use of an intra-cavity acousto-optic modulator[15] (AOM). Fig. 25 gives an illustration of the experimental configuration used. Light at 514nm from an Argon-ion laser was coupled into a 5m length of Er^{3+}-doped alumino-silica fiber through a polished end of the fiber which also provided 4% feedback for the 1.5μm signal and acted as an output coupler. Feedback at the other end of the cavity was by reflection from a flat HR mirror at 1.55μm after traversal of the AOM operating in first order mode. In this configuration, the angle of deflection of the light leaving the AOM is wavelength dependent by virtue of the dispersive properties of the acoustic grating within the AOM. Hence, narrow line feedback can be achieved by aligning the cavity for a particular wavelength. In addition, the deflection angle depends on the period of the grating and hence variation of the operating frequency of the AOM enables tuning of the device.

The output of the fiber laser consisted of a line narrowed spectrum of 0.3-1nm FWHM which was tunable over two discrete ranges centred on 1533nm and 1555nm. Fig. 26 shows the laser input/output characteristic obtained at 1533nm which corresponds to the wavelength of maximum gain in this fiber type. A threshold of approximately 350mW with a 2.7% slope efficiency was obtained. Fig. 27 indicates the tuning range of the fiber laser at the maximum pump power level of ≈850mW. The observation of discrete tuning ranges is in common with a number of other tunable Er^{3+}-doped fiber lasers described previously. The total tuning range for this laser was ≈16.5nm FWHM within an overall 33nm bandwidth. Fig. 28 shows the tuning function of the laser as a function of the AOM acoustic frequency. Of interest here is the difference in the tuning coefficient between the two discrete tuning bands. A coefficient of 3.7nm/Mhz was observed for the shorter line compared with 15nm/Mhz for the longer line. A smaller tuning coefficient may be expected for the shorter line however by virtue of the larger variation in gain with wavelength which is observed on this peak of the transition.

Of the reports of tunable, line-narrowed fiber lasers reviewed in this section two have been all-fiber ring-laser structures using polished fiber-coupler components. Of these, one report used Nd^{3+}-doped fiber operating around 1.06μm and one used Er^{3+}-doped fiber operating around 1.55μm. Three reports have demonstrated the use of intra-cavity passive bulk-optic components, Nd^{3+} and Er^{3+}-doped fibers having been tuned with a reflection grating, and Nd^{3+}-doped fiber tuned with birefringent filters. In addition, an active AOM has been incorporated into an Er^{3+}-doped fiber laser to give electronic tunability. For the Nd^{3+}-doped fiber lasers tuning ranges of 60-70 nm have been reported for each of the techniques used. For Er^{3+}–doped fibers however only one of the reports describes this degree of tunability (70nm) and this was using a high power pump source at an efficient wavelength[13].

The all-fiber ring laser structures are attractive in that the all-fiber construction provides for simplicity along with ease of alignment and low excess cavity loss. 70nm tuning with

<0.1nm output spectral width has been obtained with low threshold and reasonable slope efficiency. Choice of a more efficient pump wavelength for the Er^{3+}-doped fiber device would be likely to further improve the efficiency. However the ring-laser construction suffers a 3dB loss penalty in the output signal due to the counter-propagating laser mode which is lost. In addition, environmental stability of the coupler devices and their ability to transmit higher pump power levels will have to be assessed.

The reflection grating constructions suffer from an excess cavity loss due to insertion of the grating which has been estimated at ≈2dB [13]. This excess loss is disadvantageous in a comparatively low gain system such as Nd^{3+}-doped fibers whereby, to achieve a reasonable threshold value, substantial values of output coupler reflectivity need to be used. In this case, the grating insertion loss becomes a substantial fraction of the total cavity loss and the laser efficiency is compromised. Results published for Nd^{3+}-doped fibers have shown substantially greater efficiency when using birefringent filters as the tuning element[11] over reflection gratings[12]. For high gain Er^{3+}-doped fibers however, laser threshold can be obtained at low pump power levels with a very low reflectivity output coupler, such as a 4% fiber end reflection. In this case the grating insertion loss becomes an inconsequential proportion of the total cavity loss and efficient operation can be obtained.

The electronically tuned fiber laser described in this section has been shown to give tunability over 16.5nm FWHM in two discrete ranges around 1.55μm. It has the substantial advantage of enabling rapid scanning of the output wavelength. In addition, it would be expected that continuous tunability with a broader range would be obtainable for a more efficient pump wavelength than the 514nm wavelength used. The emission spectra in this case were relatively broad in comparison with a number of other techniques with 0.3nm - 1nm FWHM spectral widths measured. This is likely to be due to the dispersion of the cavity construction and if so, appropriate cavity design would produce narrower emission spectra.

4. Single frequency fiber lasers.

A number of techniques have been used to generate single-longitudinal-mode operation of fiber lasers, including the use of a fiber grating[16], an interferometric resonator[17], by injection locking[18] and by using a travelling-wave structure[19]. Of these approaches, three have been performed with Er^{3+}-doped fibers operating around 1.55μm and one with Nd^{3+}-doped fiber operating at 1.09μm. Each of the approaches taken for generation of single longitudinal-mode operation in fiber-lasers will be reviewed in this section.

Compared with a number of other laser types, particularly semiconductor lasers, the long cavities usually used in fiber laser structures give rise to a close longitudinal mode spacing. Obtaining stable single frequency emission from fiber lasers therefore requires cavities with substantially higher wavelength discrimination than those described earlier. The cavity must be designed such that only one longitudinal mode can oscillate. In general the longitudinal-mode showing the highest round trip gain will reach threshold first and tend to saturate the gain medium spectrally. In the spatial sense the gain medium will not necessarily be saturated however, and the excess loss imparted to other modes by wavelength selective elements must be greater than the extra gain seen by the modes due to the effect of spatial hole burning in order to ensure single longitudinal-mode operation. A number of approaches can be taken to ensure this condition. Increasing the wavelength selectivity of the cavity is one technique. In addition, decreasing the cavity length has the effect of increasing the cavity mode spacing and hence, increasing the loss seen by adjacent modes for a given degree of wavelength selectivity. Alternatively, removing the effects of spatial hole burning by operating a laser in the travelling-wave configuration can be used to generate single longitudinal-mode operation. The injection locking approach ensures that the round trip gain of the laser amplifier only reaches the threshold value for a particular frequency, which is seeded from an external narrow-band source. The injected frequency is matched to that of one of the cavity modes. Laser action in this mode then saturates the amplifier, preventing other modes from oscillating.

In the single longitudinal-mode regime, the linewidth of oscillation is determined not by the wavelength discrimination of the cavity, as in the case of line-narrowed fiber lasers, but by considerations of cavity stability and ultimately by spontaneous emission noise.

Fiber grating

Using a similar experimental set up to that shown in fig. 2, single longitudinal-mode operation of a Nd^{3+}-doped fiber laser has been obtained[16]. Using a pump wavelength of 594nm, which corresponds to strong absorption from the ground state into the $^4G_{5/2}$

level in neodymium doped glasses, a short cavity could be constructed which enabled the cavity longitudinal mode spacing to be maximised. For a total cavity length of 51mm single longitudinal-mode operation at 1.082μm was observed. A laser threshold of 7mW with respect to absorbed power and slope efficiency of 2.4% were obtained. Fig. 29 indicates a delayed self heterodyne spectrum of the laser output measured with a 2km differential path length interferometer giving 100kHz resolution. The frequency offset of 80MHz was provided with an AOM situated it one arm of the interferometer. This spectrum indicates an optical linewidth of ≈1.3MHz.

This technique has not been demonstrated with Er^{3+}-doped fibers to date. Although fiber Bragg gratings can readily be fabricated to operate as reflection filters at the erbium transition wavelength of 1.55μm, the use of short doped fiber lengths is problematic. It has been shown (see chapter II) that Er^{3+}-doped fibers show reduced efficiency with Er^{3+} concentrations above 100ppm, in contrast to Nd^{3+}-doped fibers which can readily be fabricated with concentrations of ≈1wt%. This factor may limit the operation of a single-longitudinal mode Er^{3+}-doped fiber laser constructed using this approach.

Interferometric cavity single frequency laser

An interferometric Fox-Smith type laser cavity has been successfully employed to obtain single-longitudinal-mode operation of an erbium fiber laser[17]. Fox-Smith resonators have previously been employed in bulk-optic laser configurations to enable mode selection, and this implementation shows that such a structure can be effectively used in all-fiber form with an erbium fiber laser, in combination with a reflection grating filter. The Fox-Smith characteristic gives a periodic cavity loss modulation by interference between different light paths in common with the coupled-cavity approach described in section 2. Fig. 30 shows the experimental configuration used where a single-mode fused-tapered coupler fabricated from Er^{3+}-doped fiber, two dielectric mirrors and the reflection grating were used to form the interferometric laser cavity. A path length ratio of 1.13 ± 0.02 between the two optical paths in the Fox-Smith construction was used. In this work a reflection filter was used in addition to the interferometric resonator. This enabled the overall cavity wavelength selectivity to be enhanced and enabled single-longitudinal mode operation for a path length of several metres. Such an approach of using very high wavelength selectivity has the advantage of enabling high efficiency, low-doped Er^{3+}-doped fibers can be used.

Pumping the laser with light at 514nm from an Ar^{2+} laser gave rise to the characteristic shown in fig. 31 indicating a threshold power of 175mW with a slope efficiency of 0.04%. The low value of slope efficiency was attributed in part to fiber-mirror butt losses and fiber splice losses. The wavelength of operation was measured to be 1.556μm, see fig. 32, and the spectral linewidth was measured using a Fabry-Perot interferometer to be resolution limited at 8.5MHz as indicated in fig. 33.

Injection locked fiber laser

Single longitudinal-mode operation of an erbium fiber laser has been obtained by injection-locking of the laser with an external-cavity laser diode laser[18]. In this approach a conventional fiber laser oscillator was fabricated by butting a 2.5m length of Er^{3+}-doped alumina-silica fiber to dielectric mirrors with reflectivities of 70% and 25% at 1.54μm as indicated in fig. 34. The laser was pumped with light at 528nm from an Ar^{2+} laser, a wavelength which shows reduced pump excited-state-absorption (ESA) over the 514nm Ar^{2+} line (see chapter II, Spectroscopy of Rare Earth Doped Fibers). In the free-running configuration, laser operation was observed at 1.536μm, close to the peak emission wavelength in this fiber type and no clear longitudinal-mode structure was observed with a Fabry-Perot analyzer as indicated in fig 35(a). Injecting signal from the external cavity laser diode (linewidth $\approx$100kHz) and adjusting the external signal such that its frequency was close to that of the free-running oscillator enabled locking of the erbium laser onto a single longitudinal-mode. Fig. 35(b) shows the Fabry-Perot spectrum of the fiber laser output when locked by the external signal, indicating operation on a single longitudinal-mode.

The range in frequency deviation between the injected signal and the cavity mode over which locking of the fiber-laser took place, the locking bandwidth, was investigated for this laser as a function of the ratio of signal to laser oscillator power. This characterisation was performed by linearly scanning the cavity mode frequency with the use of a piezo-electric modulator whilst keeping the external signal frequency constant. The locking bandwidth was then determined by observing the duration of locked operation with the Fabry-Perot analyzer. Fig. 36 shows the locking bandwidth as a function of signal to oscillator power showing an increase in locking bandwidth with injected signal power in good agreement with a theoretical prediction.

It was noted in this work that environmental temperature changes caused the laser to drift out of the locking bandwidth by varying the fiber-laser mode frequency. In order to stay within a locking bandwidth of 3MHz, very accurate temperature stabilisation of the fiber, or more practically, active mode-frequency stabilisation involving feedback was suggested.

Travelling-wave fiber laser

A travelling-wave erbium-fiber laser has been fabricated which operated on a single longitudinal mode by removing spatial hole-burning within the gain medium[19]. Fig. 37 shows the experimental configuration used along with diagnostic equipment used for spectral analysis. A ring-laser cavity which gave substantial differential loss between CW and CCW waves was fabricated by splicing a pigtailed polarisation independent isolator and a 1m length of alumino-silicate fiber between two ports of a dichroic fused-tapered coupler. The coupler was fabricated to substantially couple pump light at 980nm with only small coupling at 1540nm. In the ring laser configuration, pump light can be effectively coupled into the laser while a degree of coupling at 1540nm provides the output coupling for the laser. The total resonator length was ≈4m.

Fig. 38 show the laser characteristic when pumped at 980nm. A threshold of 6mW and 2.3% slope efficiency were observed. The relatively low value of slope efficiency for 980nm pumping was ascribed to non-optimum output coupling provided by the coupler associated with an excess loss of the cavity of ≈3dB. The excess loss was a combination of isolator loss and splice loss between non-matched fibers.

Without optimisation of the loop polarisation controller the laser was seen to oscillate in a number of modes, typically 2-4 widely spaced modes as determined by examination of monochromator and Fabry-Perot spectra. With optimisation however, a single longitudinal mode could be selected as confirmed by Fabry-Perot spectra. Adjustment of the loop birefringence was believed to optimise the overlap between the cavity modes and slightly polarisation anisotropic gain. The wavelength of operation of the laser was determined to be 1.555μm, and the mode linewidth was determined with the use of a conventional delayed self-heterodyne spectrum analyzer. Fig. 39 shows the self-heterodyne spectrum indicating a linewidth of ≈60kHz along with the instrument limited Fabry-Perot spectrum. The symmetric double peaks in the self-heterodyne spectrum were due to relaxation oscillations in the erbium laser, partially excited by noise in the laser pump source.

To summarise this section, a number of approaches have been taken for obtaining single longitudinal-mode operation in fiber lasers. One approach has been to use a fiber grating reflection filter with a short cavity length to maximise the longitudinal mode spacing[15]. This work used Nd^{3+}-doped fiber in an overall cavity length of 51mm and produced a single longitudinal-mode output at 1.082μm with a spectral width of 1.3MHz. Although attractive for Nd^{3+}-doped fiber laser devices which can be fabricated with high Nd^{3+} ion concentrations, the reduced efficiency of Er^{3+}-doped fibers at high concentrations (see chapter II) may limit the use of Er^{3+}-doped fibers in such a configuration.

Increasing the wavelength sensitivity of the cavity loss has enabled a substantially longer laser to be constructed with Er^{3+}-doped fiber which gave single longitudinal-mode operation[16]. In this case an interferometric Fox-Smith type cavity used in conjunction with a bulk grating reflection filter gave the required wavelength sensitivity. Problems associated with residual fiber birefringence in such a fiber cavity can be solved with the use of highly birefringent fiber and coupler. Mode-hopping due to temperature variations in the cavity optical path length may be a more serious problem associated with using fiber cavities with relatively narrow longitudinal mode spacing.

Single frequency operation of an injection locked Er^{3+}-doped fiber laser around 1.55μm with a relatively long 2.5m cavity has also been described. Again here, ambient temperature variations will limit the time duration over which locking takes place although using feedback stabilisation may be possible.

Elimination of spatial hole-burning by operating an Er^{3+}-doped fiber laser in a travelling-wave ring configuration has also produced single longitudinal-mode operation. In this case the cavity length was 4m and the emission linewidth was measured to be $<$100kHz at 1.55μm. In this work variations in fiber birefringence due to temperature variations was seen to affect the stability of the laser emission. Again here, highly birefringent fibre components would improve the stability. However, mode hopping due to temperature variations in the optical path length are also likely to be problematic in common with other long fiber resonator structures.

5. Summary

A number of approaches to the generation of narrow linewidth emission from fiber lasers have been described in this chapter. These have included the use of bulk and fiber passive components as well as acousto-optic devices and injection locking with an external signal source. In a number of cases, single-frequency emission has been obtained and tunable, narrow-linewidth (<0.1nm) operation has been demonstrated.

A clear result of a number of the experiments described here is that the fiber laser configuration can be effectively used to obtain tunable laser emission over a large fraction of the emission lines of rare-earth species doped in glass media. This results from the high optical confinement associated with single mode fibers enabling laser action even with small emission cross sections such as observed in the wings of the emission lines. 70nm tuning ranges have been demonstrated for both neodymium and erbium doped silica fibers. The use of fiber couplers are an attractive means of tuning such lasers, obviating optical alignment problems associated with bulk components and efficient devices have been demonstrated using these components. Environmental stability of the polished coupler characteristics is an issue which would have to be addressed however if such devices were to be widely used. Most structures have been mechanically tuned, however the use of an AOM as a tuning element has demonstrated a technique which allows for rapid wavelength scanning by electronic means.

Narrow-linewidth operation of fiber lasers using fiber Bragg reflection gratings has been demonstrated around 1.06μm and 1.55μm, offering high efficiency. This approach is attractive for generating emission at a precise pre-determined wavelength, which will be of interest for a number of applications, but has not been demonstrated to offer any significant tunability. Another scheme which has produced narrow-linewidth emission, namely the use of intra-cavity etalon may enable a degree of tunability in the output of the laser. Etalons are currently commercially available which offer very high finesse (>10,000) and wide piezo-electric tunability (8000GHz) which could find application in such a fiber laser configuration.

For single-frequency operation a number of very different approaches have been taken. The use of a fiber grating filter has been extended to single frequency operation at 1.06μm by using a very short cavity which maximises the longitudinal mode spacing. This technique is attractive in that it enables a high degree of stability in the output spectrum. Other techniques such as Fox-Smith and travelling-wave cavities, in addition to the injection locking scheme described, will generally subject to fiber birefringence and temperature variations. Fabrication of such devices from highly-birefringent fiber and polarisation preserving coupler components will improve the stability of these devices.

For the future, the ease with which narrow-linewidth tunable fiber lasers make a transition from laboratory benches into commercial devices depends to a certain extent on the development of additional components. Certainly, the results published to-date indicate the potential for these devices with 50% efficient laser characteristics, 70nm tunability around 1.55μm and sub 100kHz linewidths obtainable. A number of devices hold certain promise for providing the necessary characteristics for line-narrowing and tuning of fiber lasers. High finesse Fabry-Perot cavities have already been mentioned. Integrated-optic acoustically tunable filter devices[20] also appear very attractive. Such devices offer very broad tunability, >100nm, with passbands of order 1nm. The use of such a device in an erbium travelling-wave fiber laser for example offers the potential of a compact and tunable single frequency source around 1.55μm.

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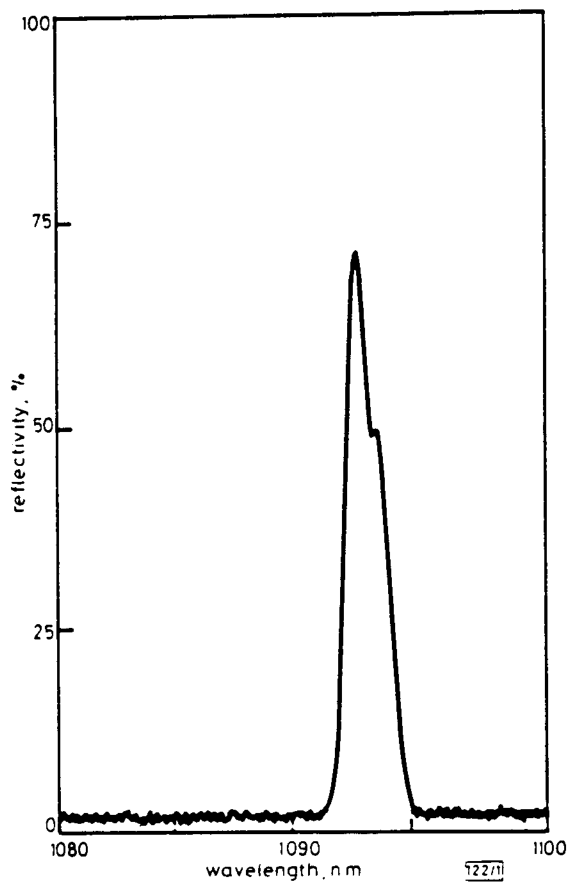


Fig. 1 *Reflection characteristic of a typical fibre grating, similar to that used in the experiment*

Fig 1

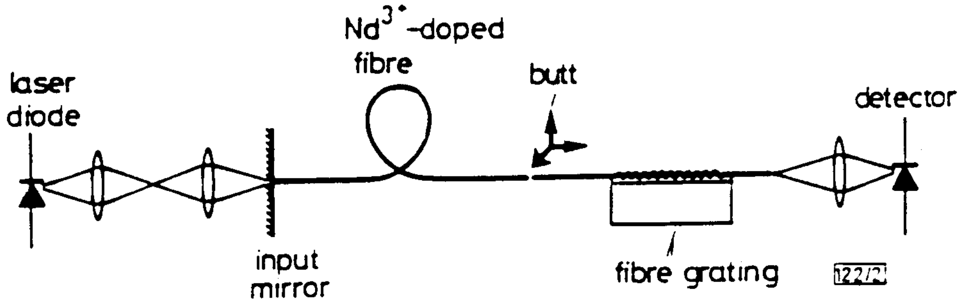


Fig. 2 *Experimental configuration of fibre laser using fibre grating*

Fig 2

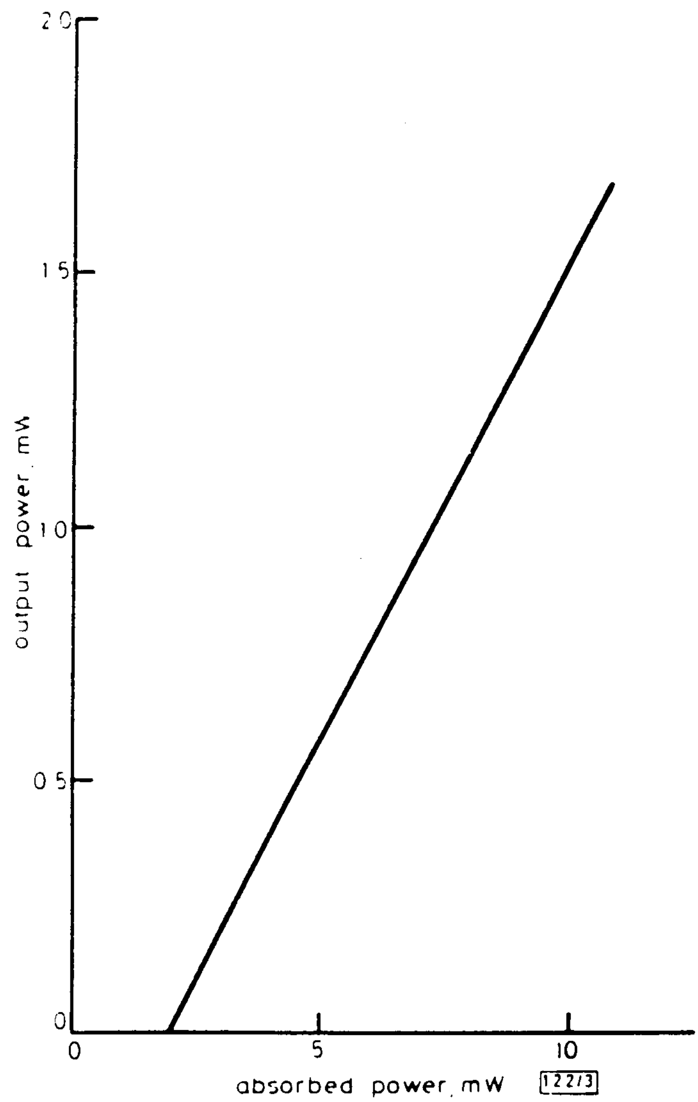


Fig. 3 *Nd^{3+}-doped single-mode fibre laser characteristic using fibre grating and 830 nm diode laser pump*

Fig 3

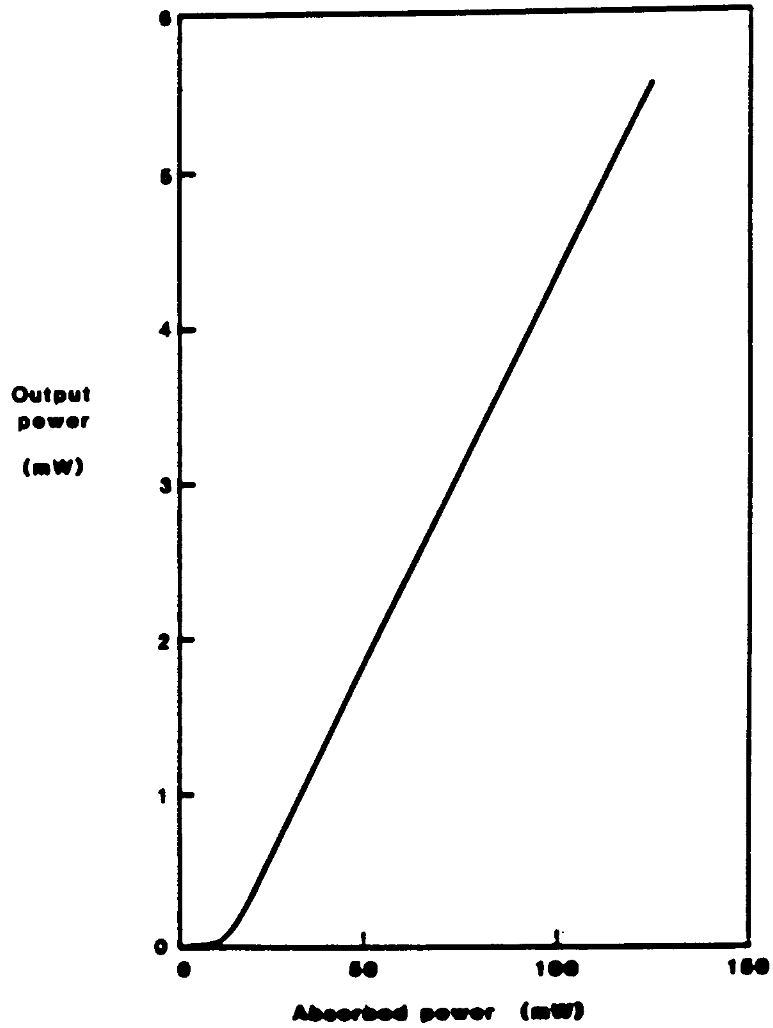
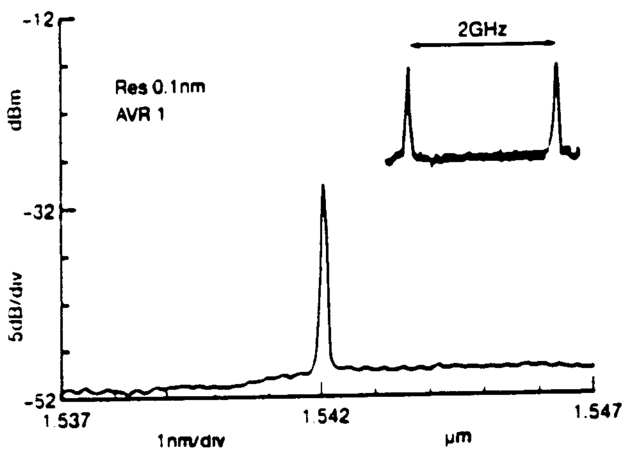


Fig. 3. Er^{3+}-doped single-mode fiber-laser characteristic using fiber grating and 650-nm dye-laser pump.



TUG4 Fig. 3. Output characteristics of an Er^{3+} doped silica fiber laser, which has a *D*-fiber reflection filter as one feedback element. Lasing at 1.542 μm is shown by the diffraction grating spectrum analyzer trace, while the inset shows <20-MHz linewidth resolution limited by the 2-GHz FSR scanning Fabry-Perot used.

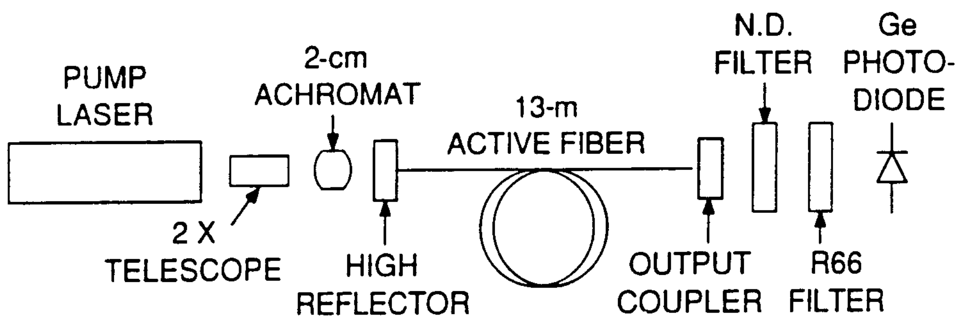


Fig. 1. Block diagram of the fiber laser and the experimental apparatus. N.D., neutral-density.

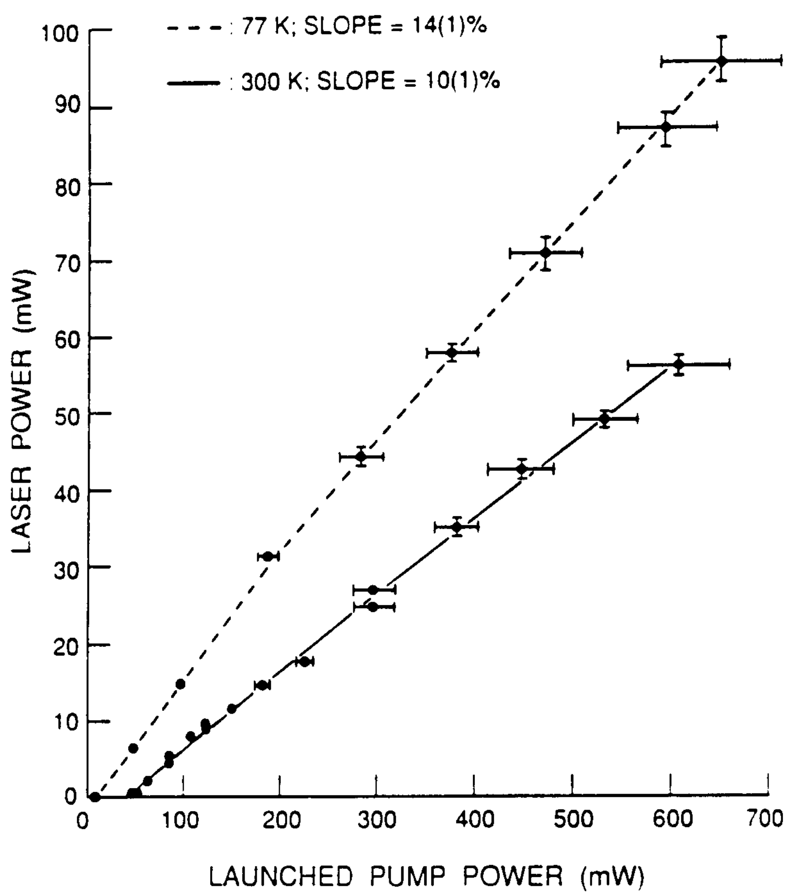


Fig. 2. Laser output power versus the launched pump power measured at 300 K (solid curve) and 77 K (dashed curve).

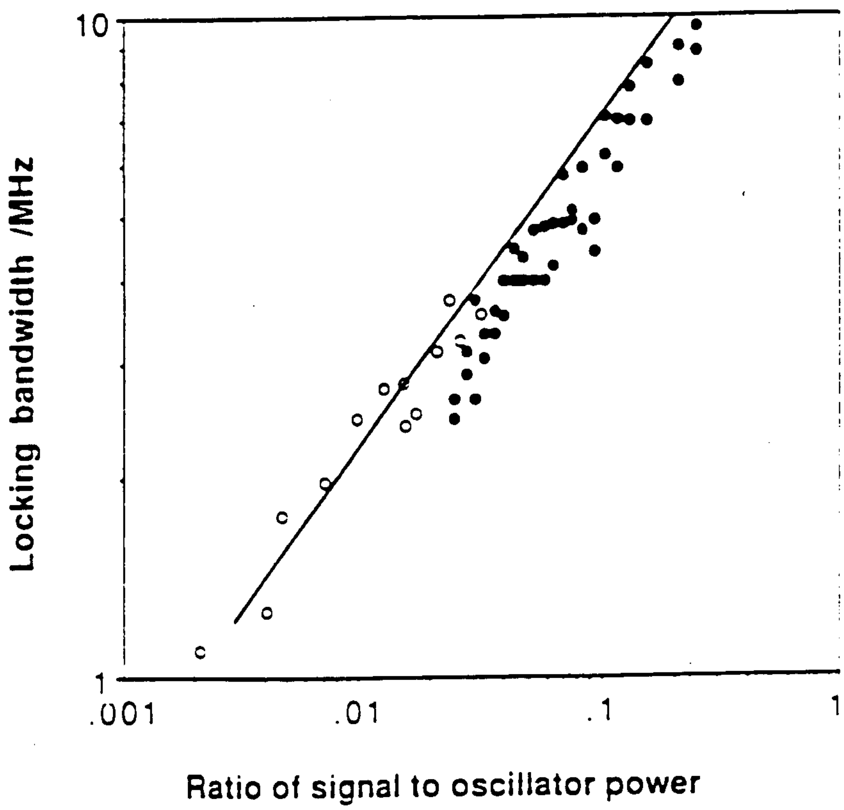


Fig. 4. Locking bandwidth as a function of the ratio of injected signal to free running laser intensity (I_1/I_0). ○: fixed pump power. varying injected signal power: ●: varying pump power. fixed injected signal power: —: theoretical prediction.

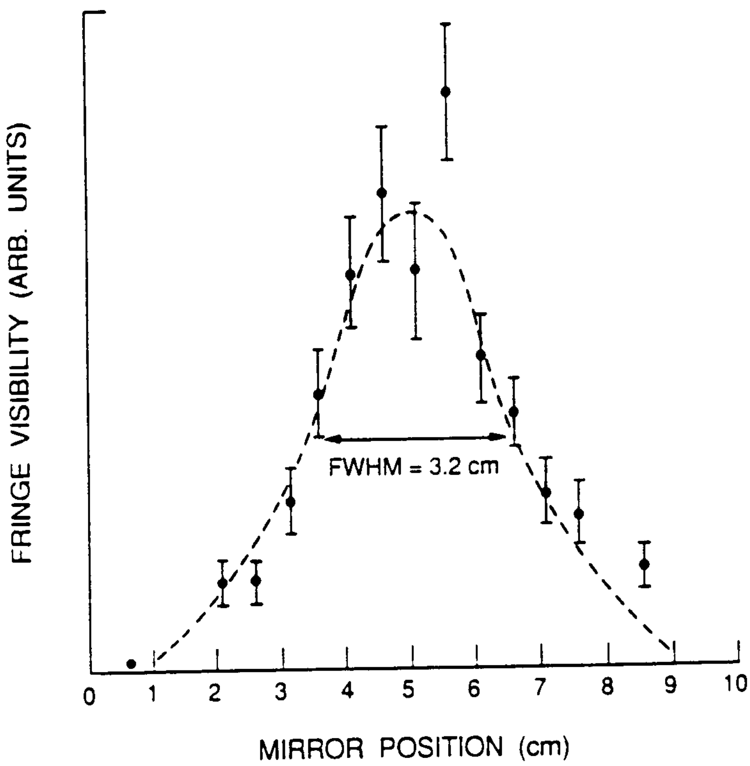


Fig. 5. Interferometric measurement of the output coherence length showing the fringe visibility as a function of the movable mirror position. The FWHM of the fitted Gaussian curve (dashed curve), 3.2 ± 0.3 cm, corresponds to a laser linewidth of 620 ± 60 MHz.

Fig 8

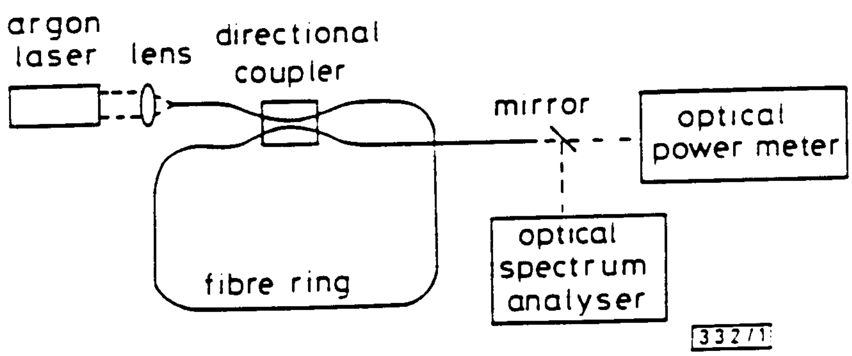


Fig. 1 *Experimental set up*

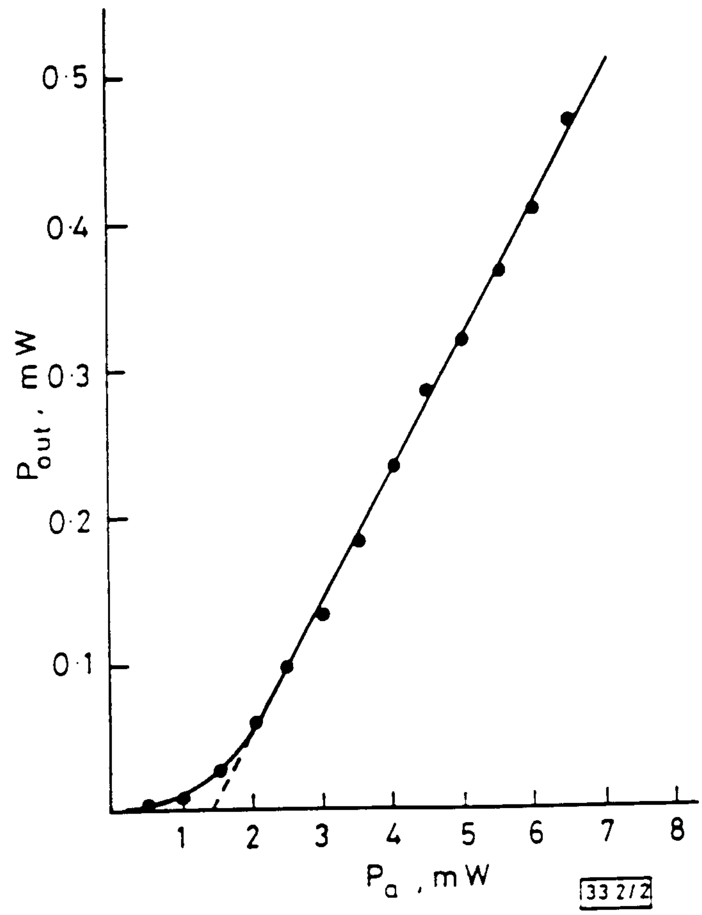


Fig. 2 *Lasing characteristics*

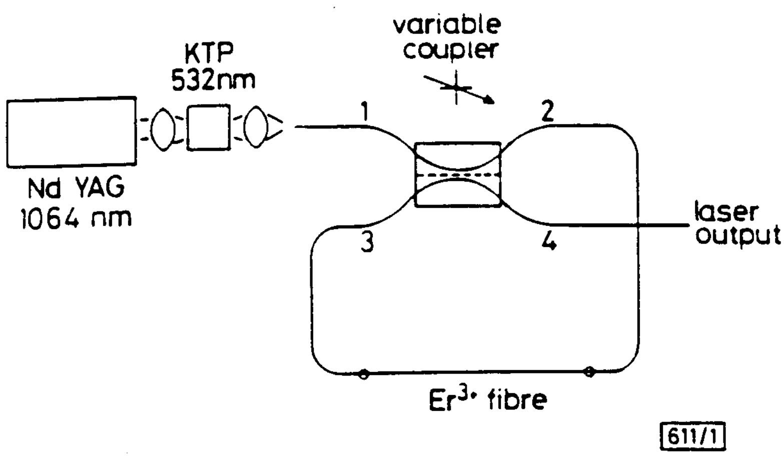


Fig. 1 *Experimental layout*

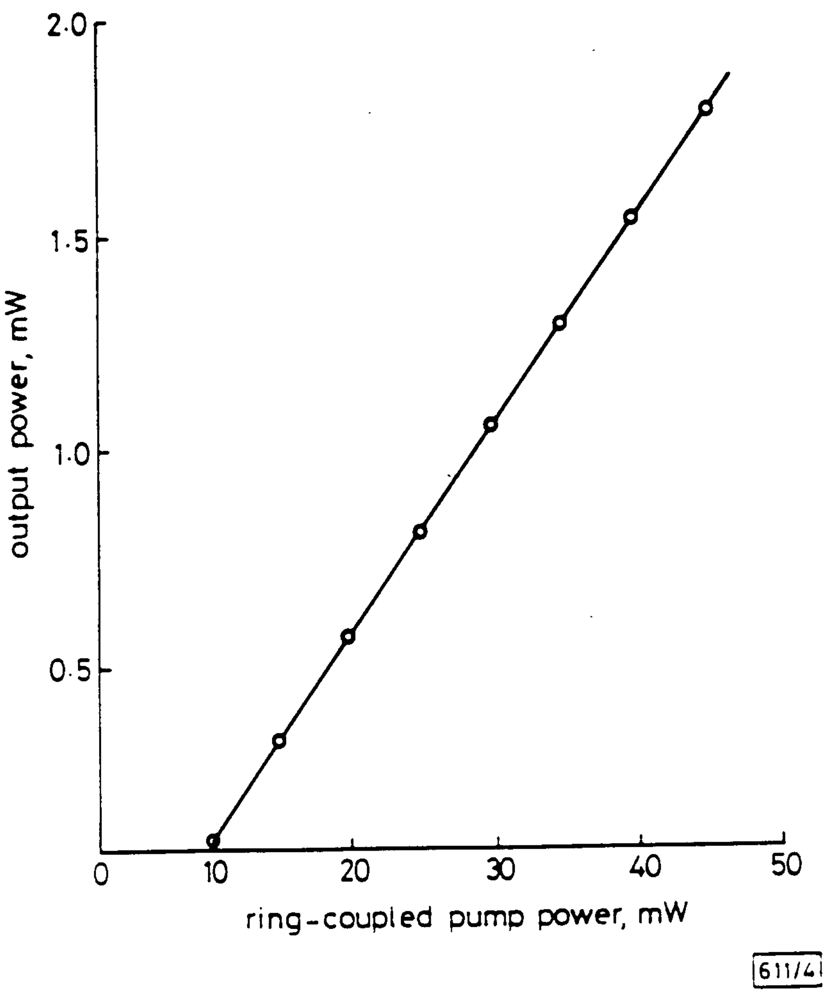


Fig. 4 *Laser characteristic*

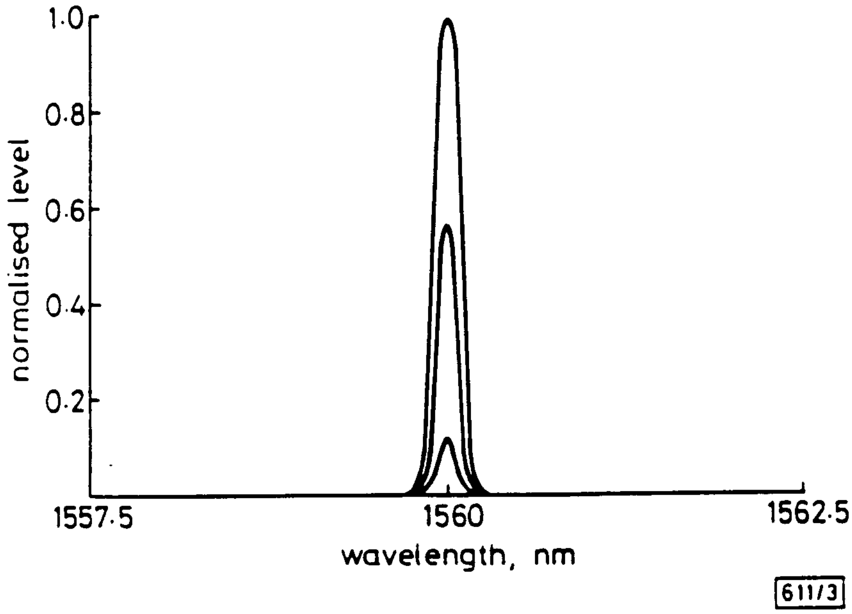


Fig. 3 *Laser output*

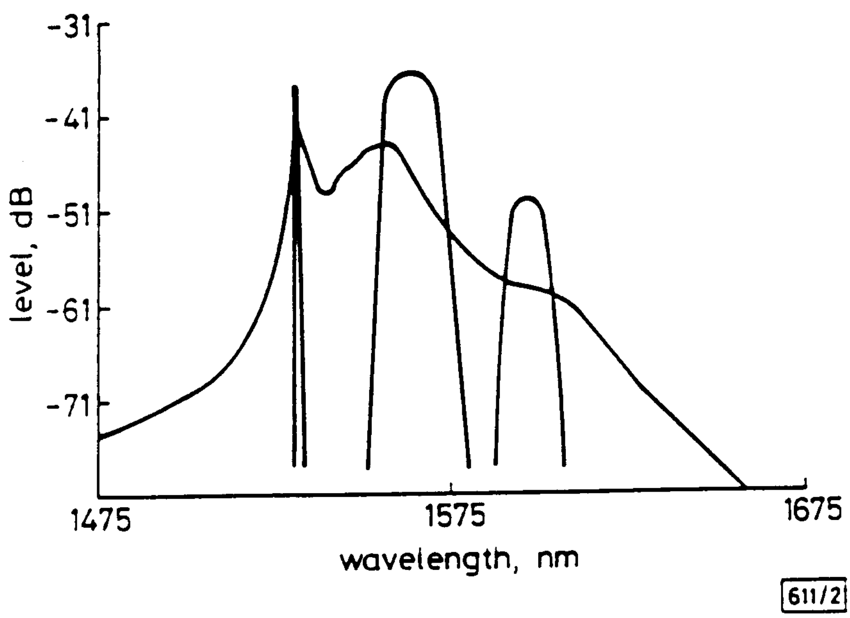


Fig. 2 *Fluorescence and tuning bands*

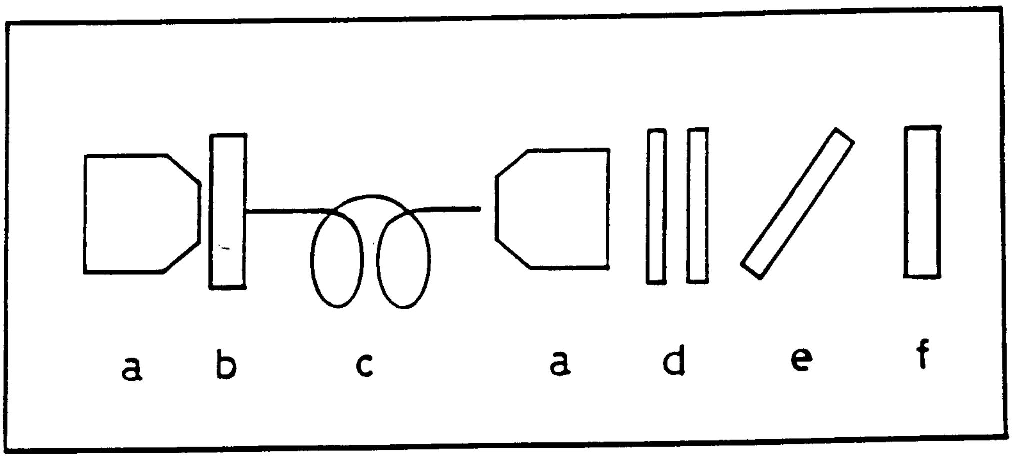


Figure 1. Schematic diagram of fibre laser cavity

a Microscope objective
b High reflector
c Doped fibre
d Quarter-wave plates
e Birefringent filter
f Output coupler

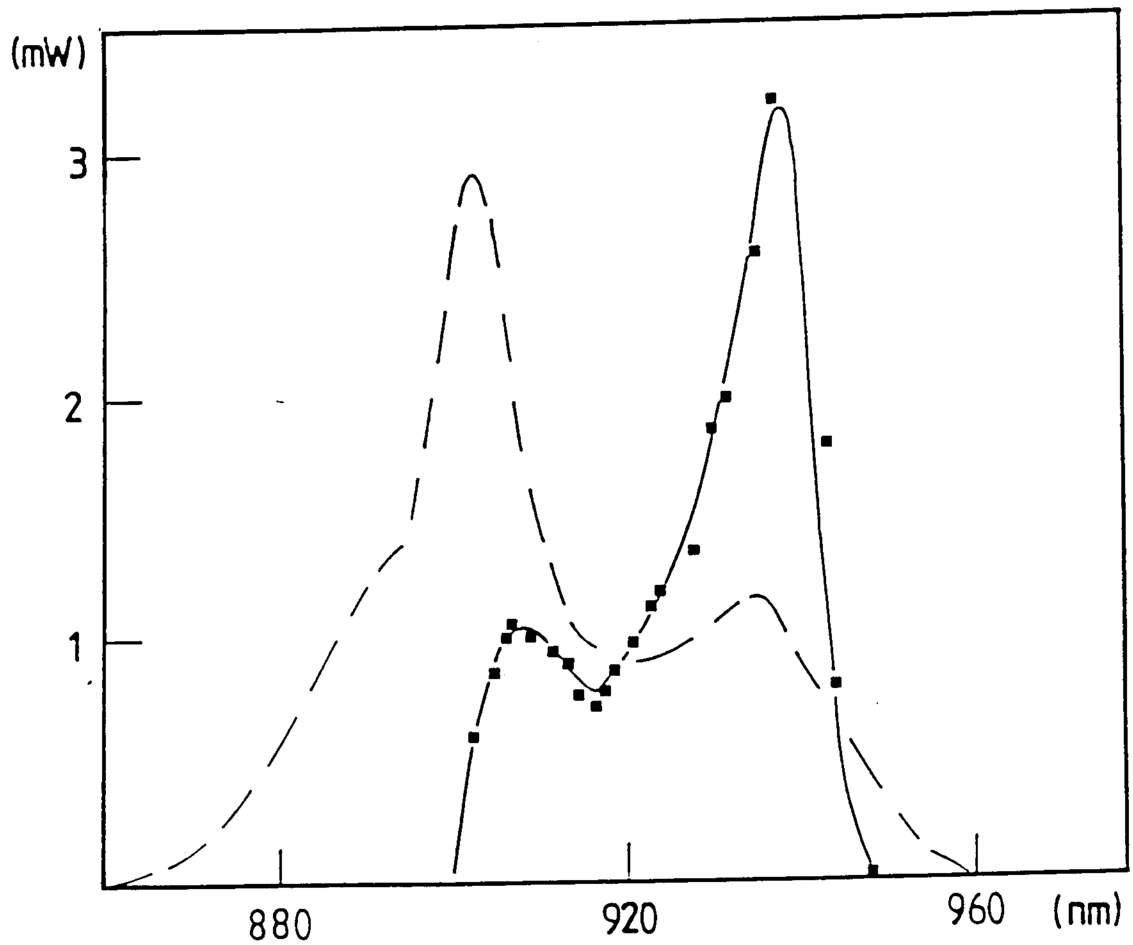


Figure 2. Photoluminescence spectrum (dotted line) and laser output power variation with wavelength (solid line) for the $^4F_{3/2}$ - $^4I_{9/2}$ transition. (The photoluminescence spectrum is not corrected for material reabsorption.

Fig 16

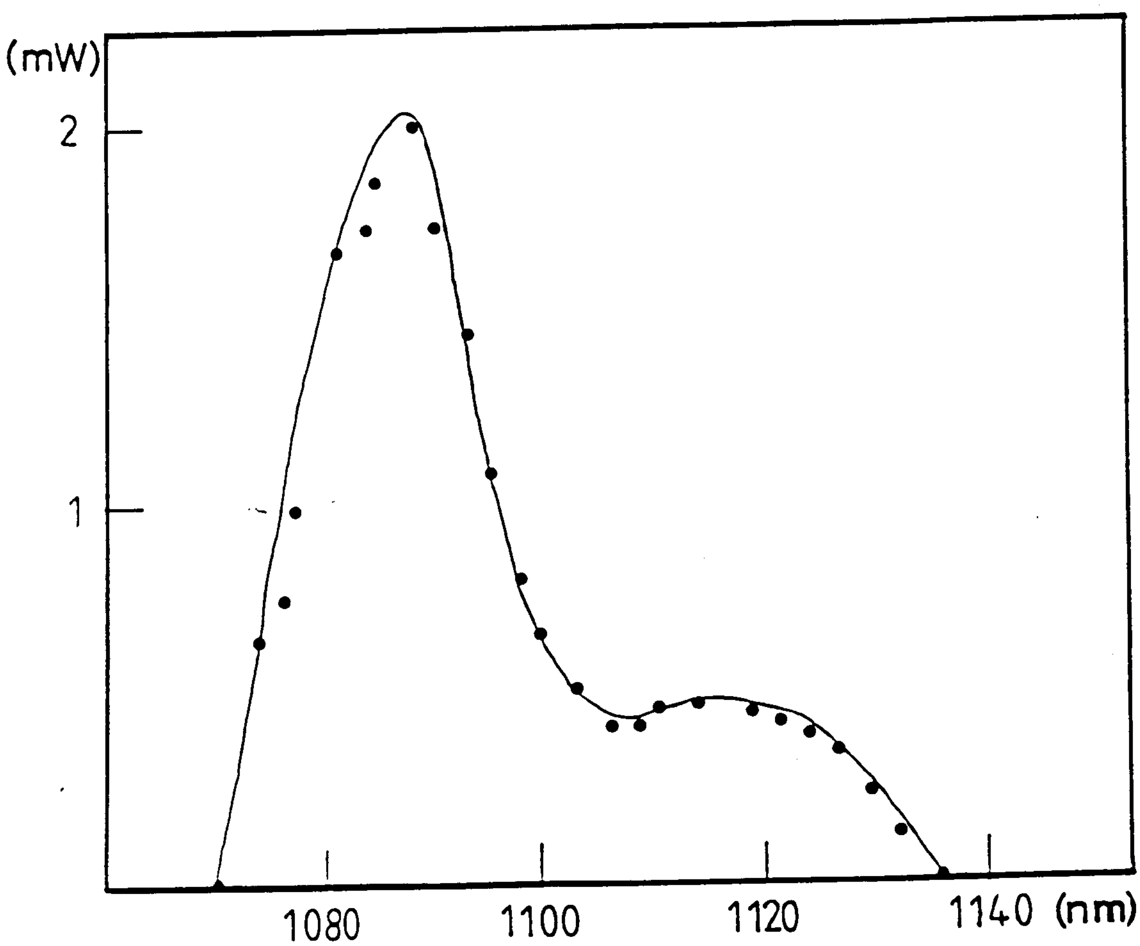


Figure 3. Laser output power variation with wavelength for the $^4F_{3/2}$ - $^4I_{11/2}$ transition.

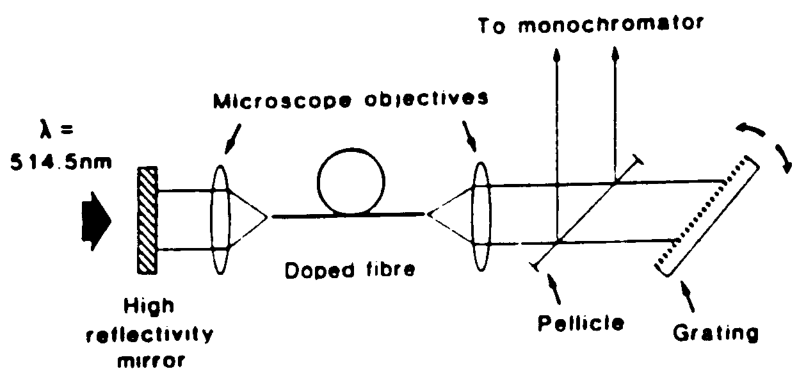


Fig. 5. Experimental configuration of tunable Nd^{3+}-doped single-mode fiber laser.

Fig 18

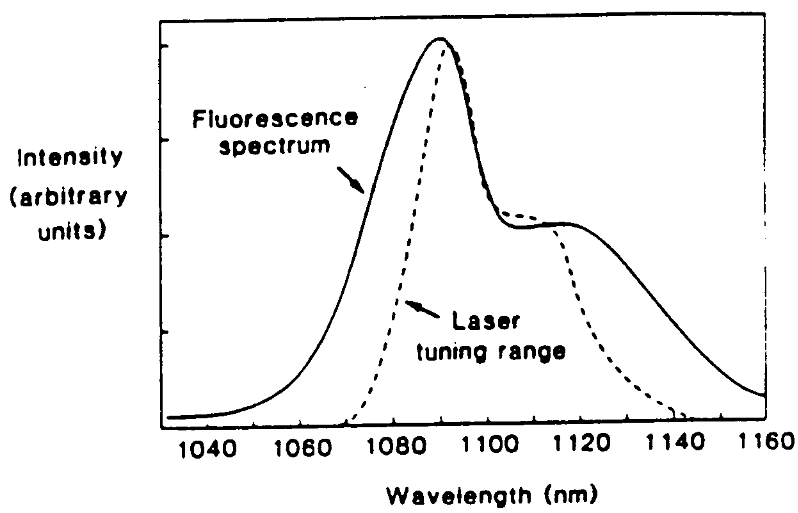


Fig. 7. Laser tuning range and fluorescence spectrum of Nd^{3+}-doped single-mode fiber laser.

Fig 19

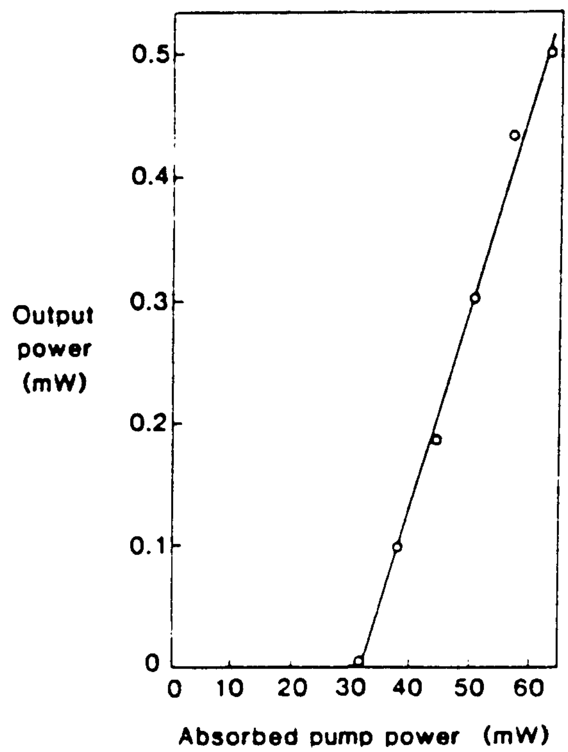


Fig. 6. Lasing characteristic of tunable Nd^{3+}-doped single-mode fiber laser.

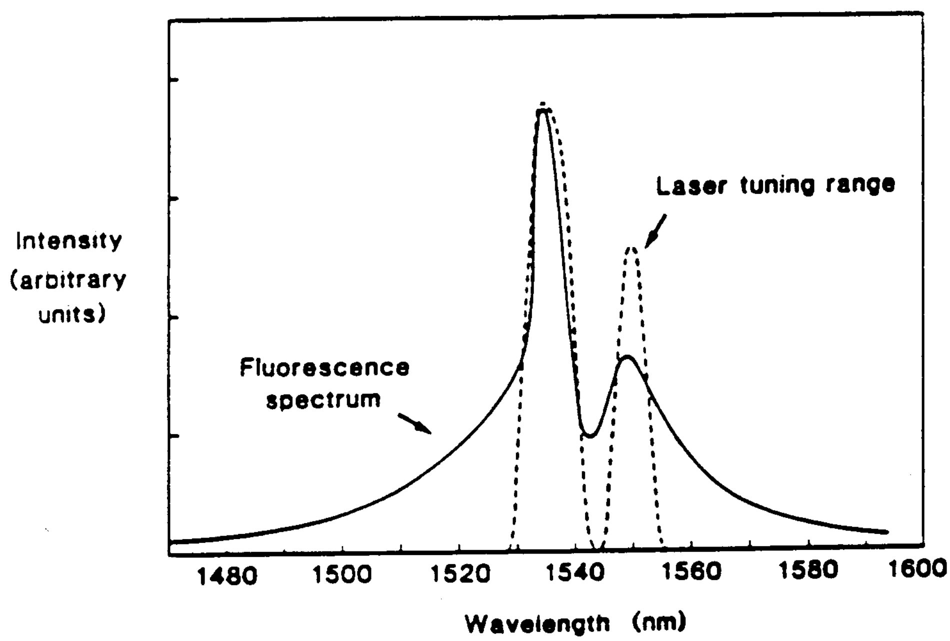


Fig. 11. Laser tuning range and fluorescence spectrum of Er^{3+}-doped single-mode fiber laser.

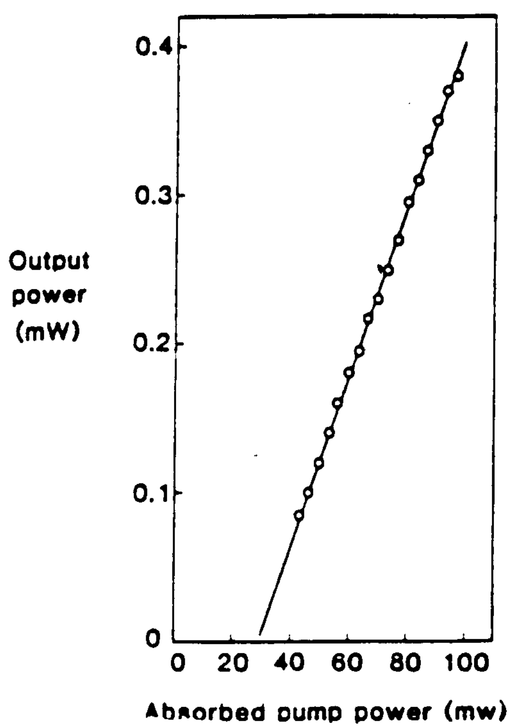


Fig. 10. Lasing characteristic of tunable Er^{3+}-doped single-mode fiber laser.

Fig 22

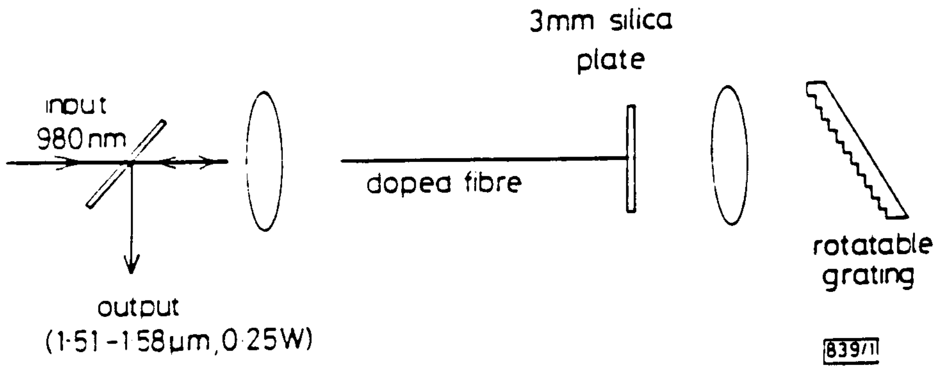


Fig. 1 *Experimental arrangement*

Fig 23

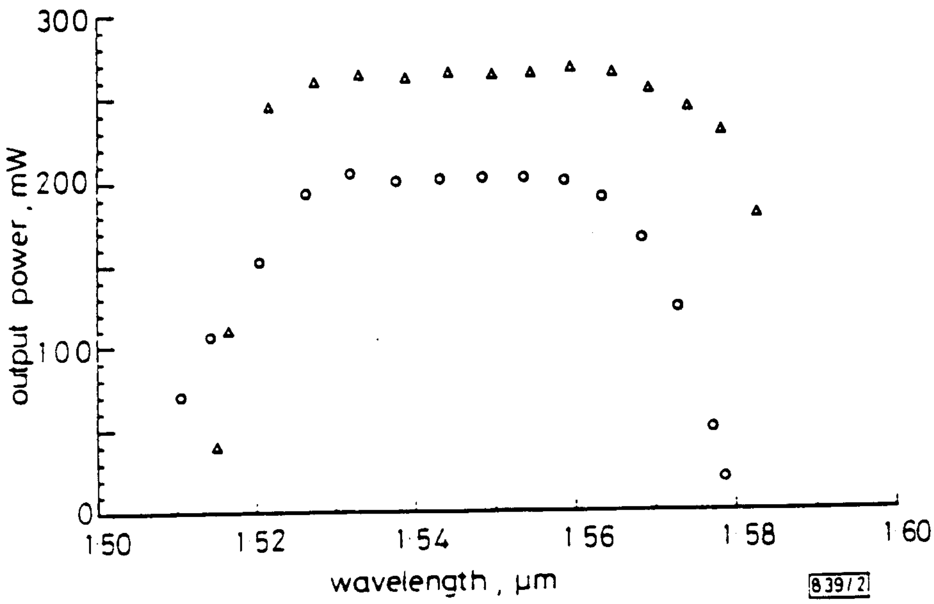


Fig. 2 *Output power as function of wavelength for 540 mW launched power at 980 nm*

Fibre length is 5·5 m (○) and 9·5 m (△)

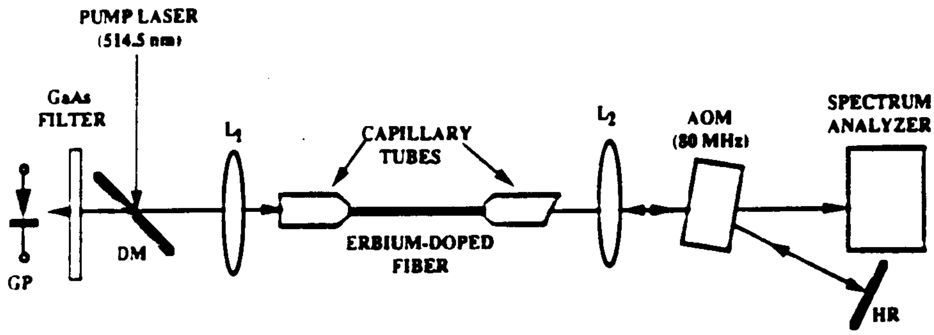


Fig. 1. Experimental setup used to tune an erbium-doped fiber laser acousto-optically and to measure its output power and spectrum: DM, dichroic mirror that reflects 99% at 514.5 nm and transmits 85% at 1.55 μm; L_1, L_2, 18X and 10X objectives, respectively; HR, high reflector at 1.55 μm; GP, germanium photodetector.

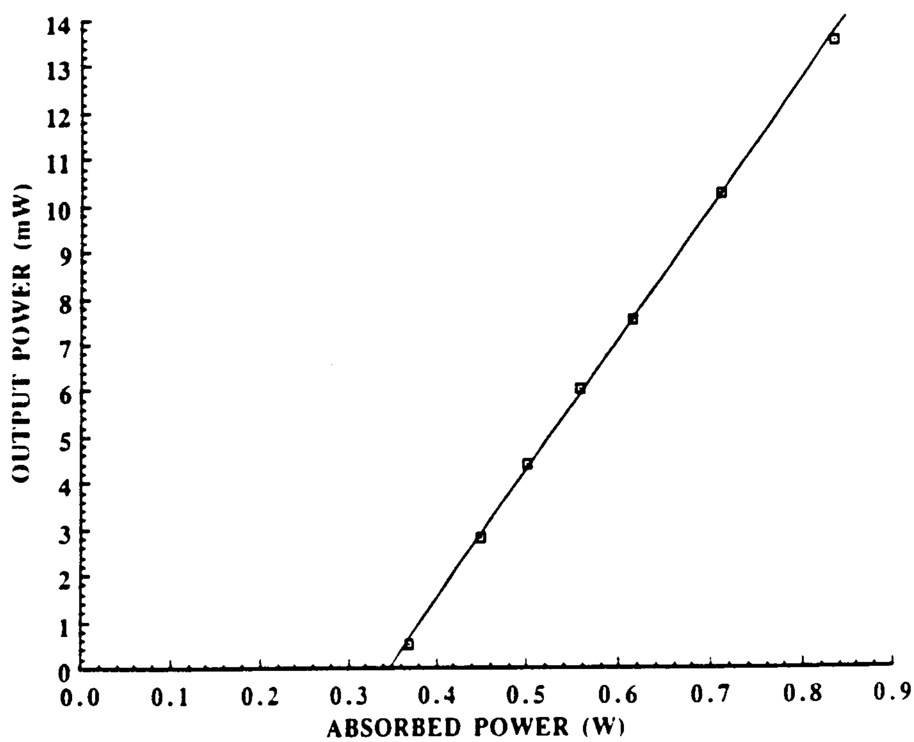


Fig. 3. Measured laser power curve for the highest-power wavelength of the tunable erbium-doped fiber laser source demonstrated.

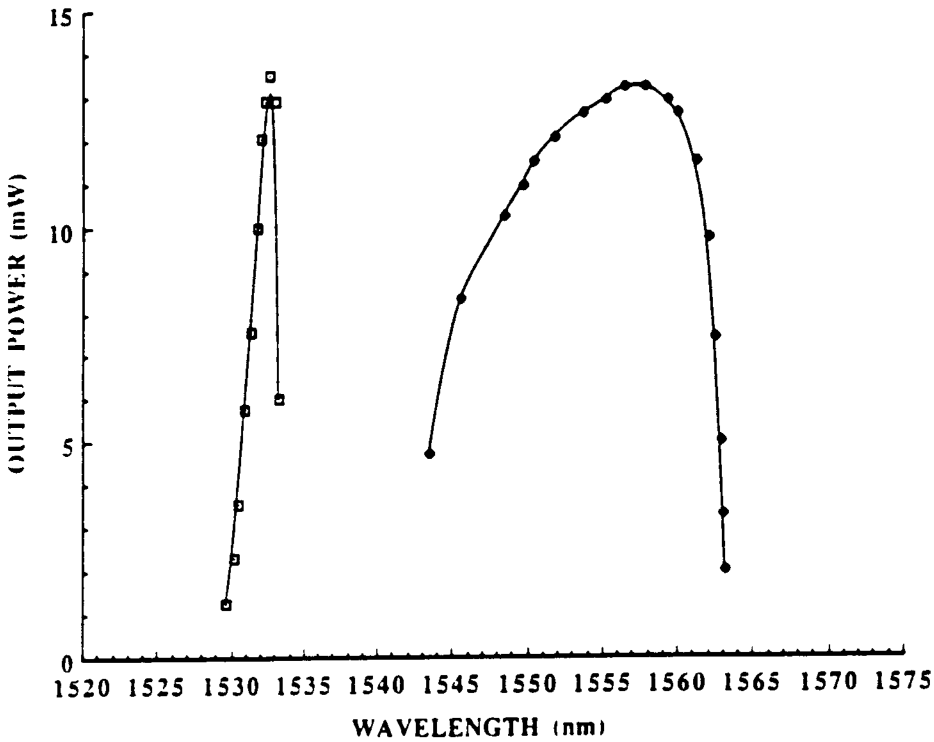


Fig. 5. Power tuning curve measured for the AOM-tuned erbium-doped fiber, showing its output power as a function of signal wavelength at maximum pump power.

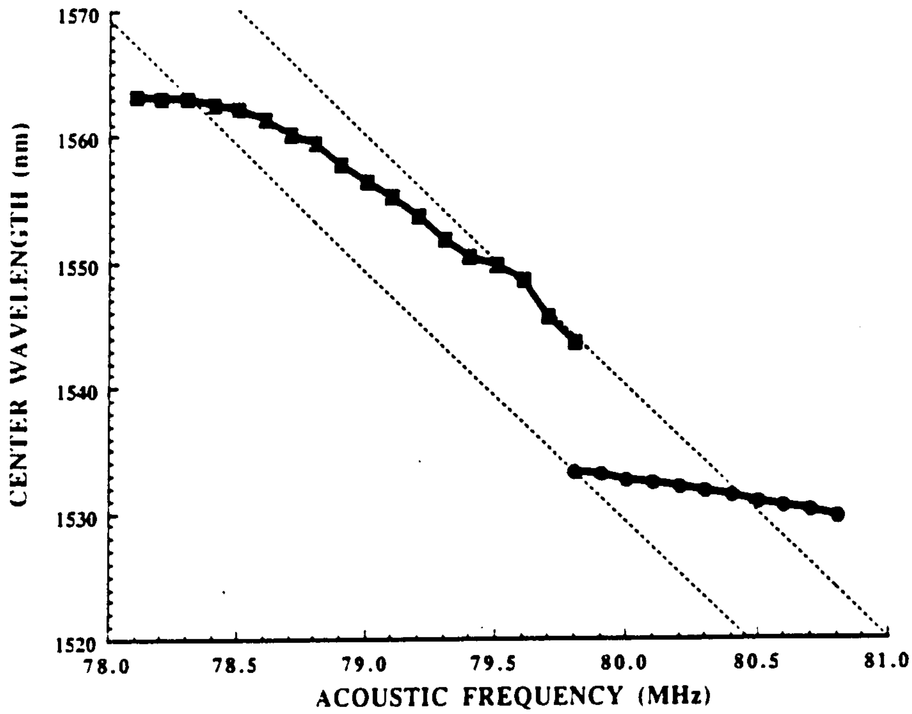


Fig. 4. Center wavelength of observed laser lines as a function of AOM acoustic frequency. The dashed lines indicate a proposed tuning system passband (FWHM) for each modulator frequency with the calculated slope and tuning system passband width for this system.

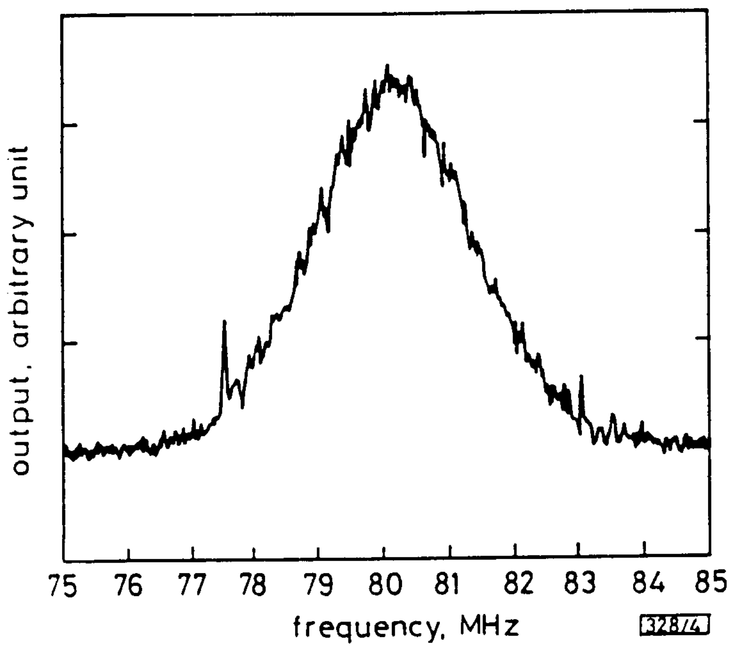


Fig. 4 *Self-heterodyne interferometer RF spectrum of single-longitudinal-mode fibre laser*

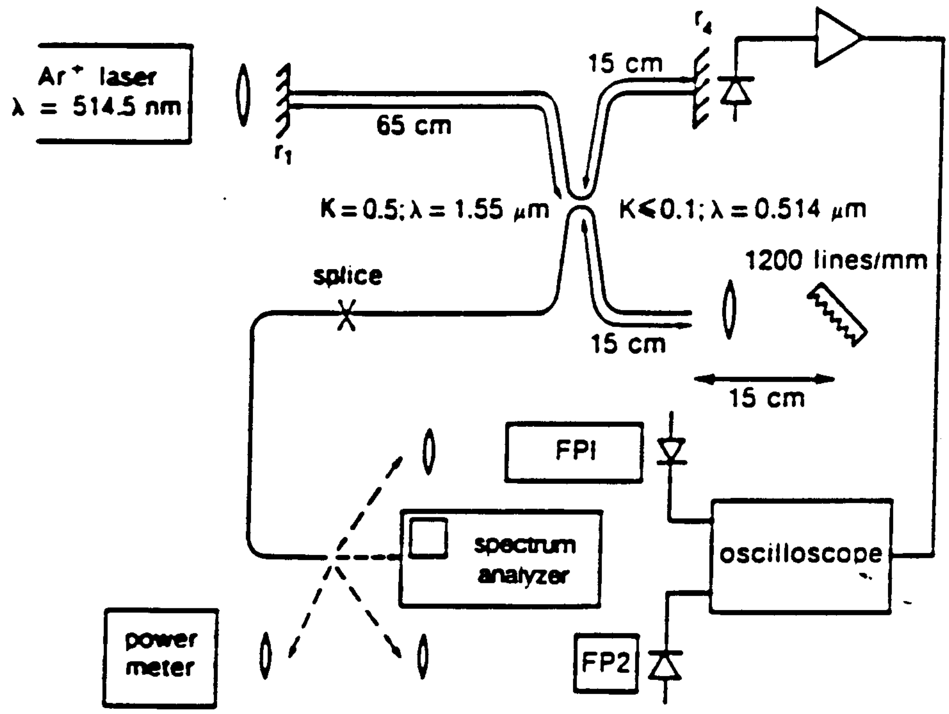


Fig. 8. Experimental equipment for producing and detecting single-longitudinal-mode output from a Fox–Smith fiber laser. The spectrum analyzer is an Anrizu model MS96A. Details of the constituent parts of the Fox–Smith laser are given in Section 6. FP1, FP2, Fabry–Perot interferometers.

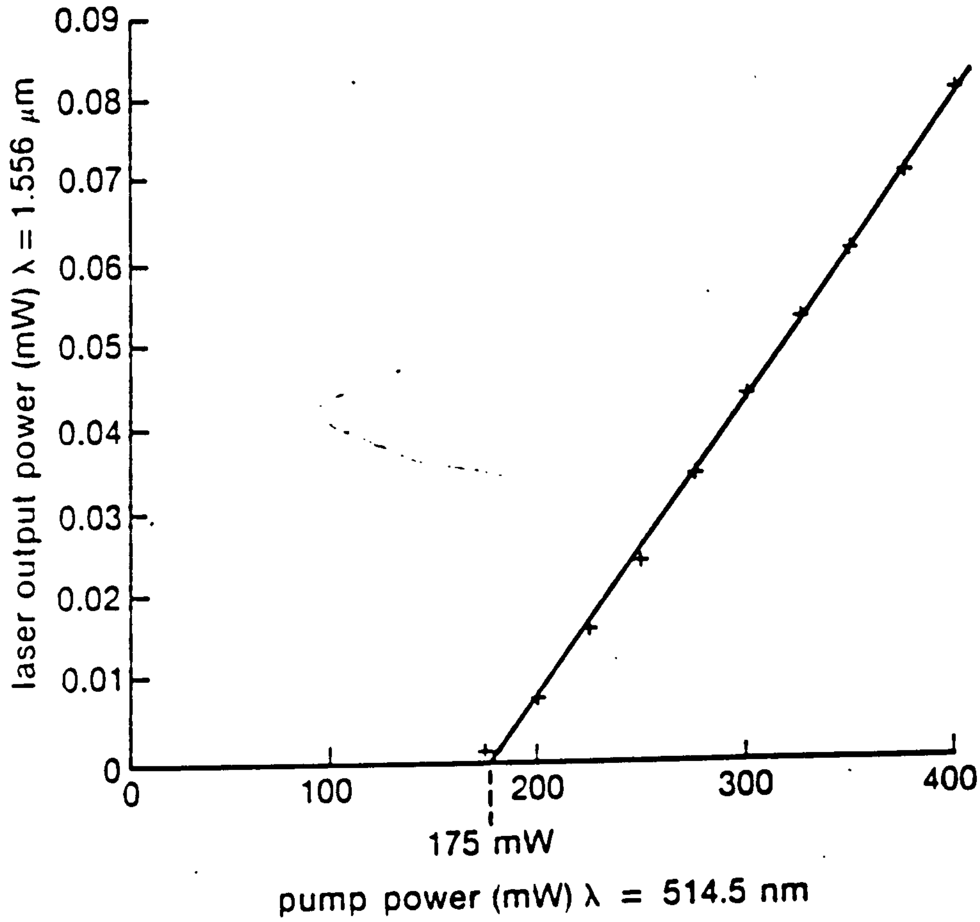


Fig. 10. Variation of fiber Fox–Smith laser output as a function of the output power of the argon-ion laser.

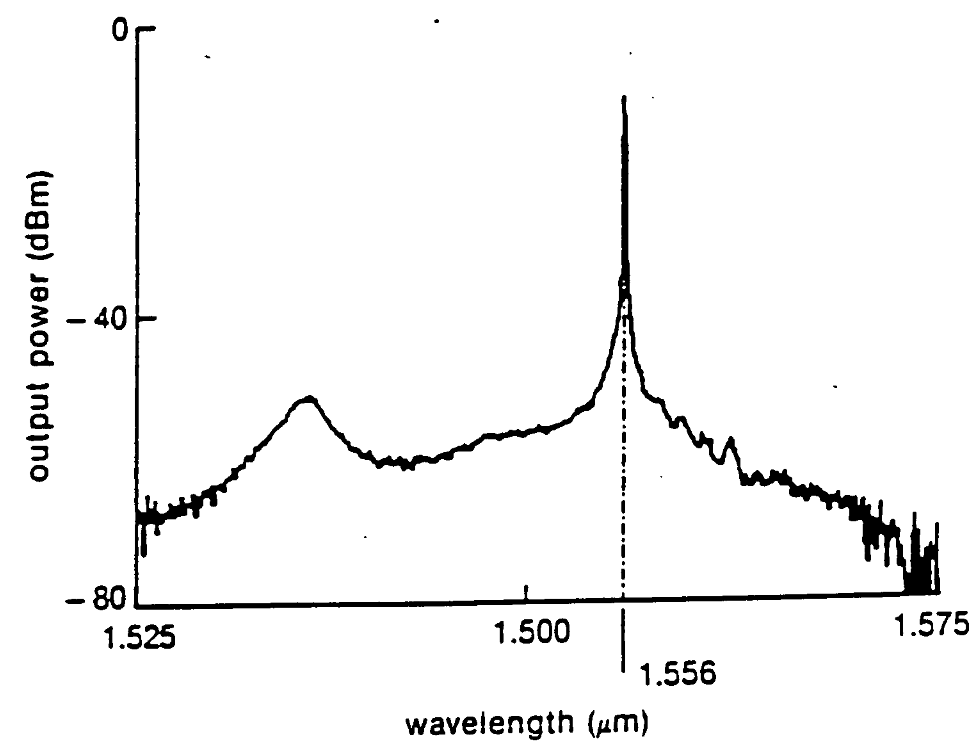


Fig. 9. Output from the optical spectrum analyzer. The vertical scale is logarithmic. Argon-ion laser output power is 350 mW.

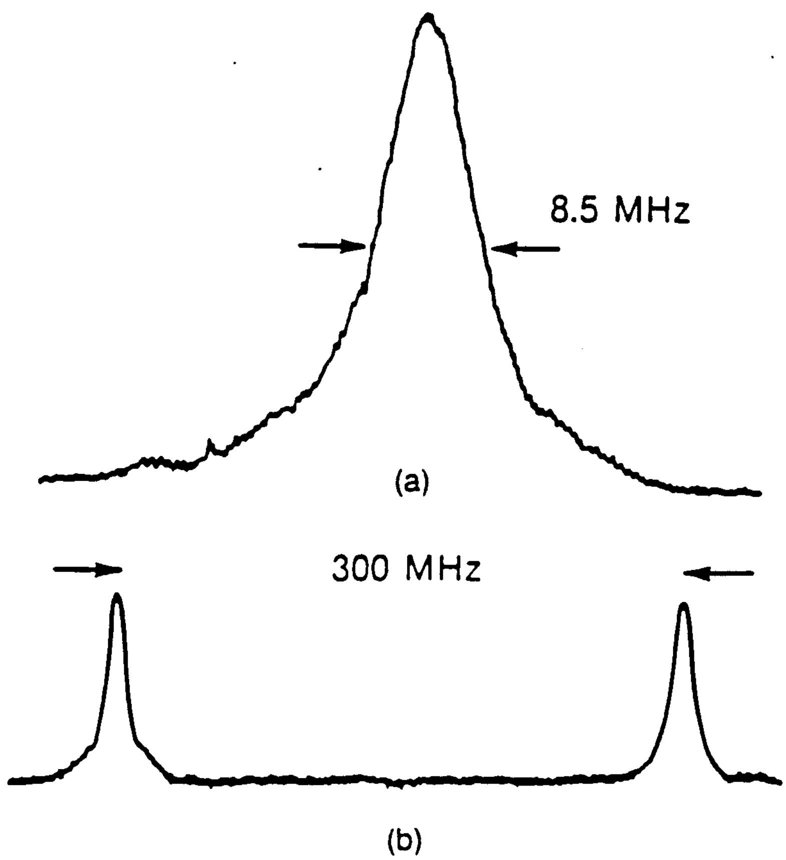


Fig. 12. (a) Spectral linewidth of Fox–Smith fiber laser limited by the passive linewidth. (b) Response of a Fabry–Perot interferometer, showing a free spectral range of 300 MHz.

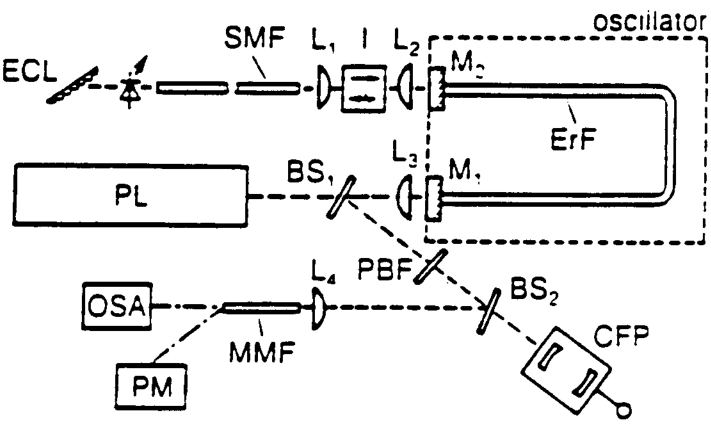


Fig. 1. Experimental arrangement. ECL: external cavity diode laser; SMF: single mode fibre; L_1, ..., L_4: lenses; I: optical isolator; M_1, M_2: mirrors; ErF: erbium doped fibre; BS_1, BS_2: beamsplitters; PBF: pump wavelength blocking filter; MMF: multimode fibre; OSA: optical spectrum analyser; PM: power meter; CFP: confocal Fabry-Perot interferometer; PL: pump laser.

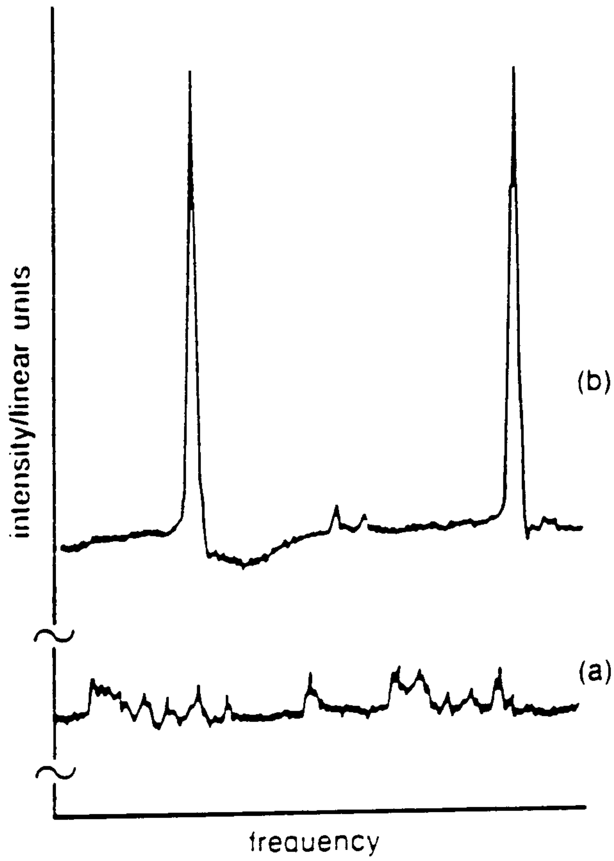


Fig. 2. Oscillator spectrum obtained with scanning CFP (a) without and (b) with injected signal.

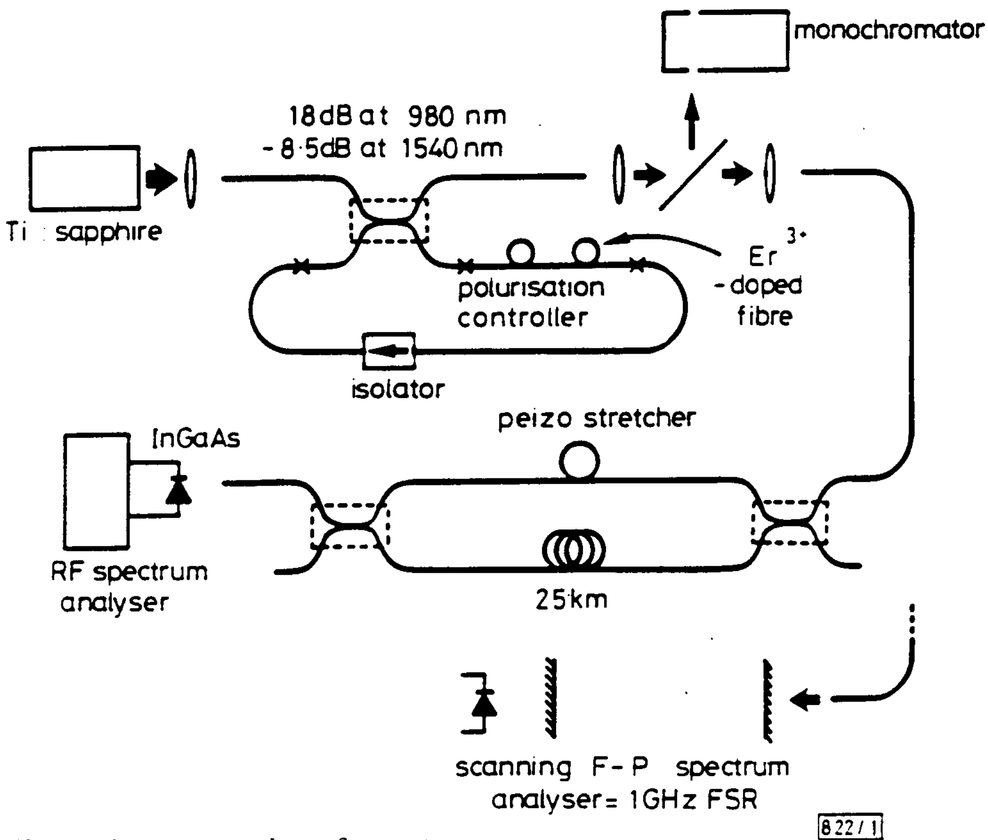


Fig. 1 *Experimental configuration*

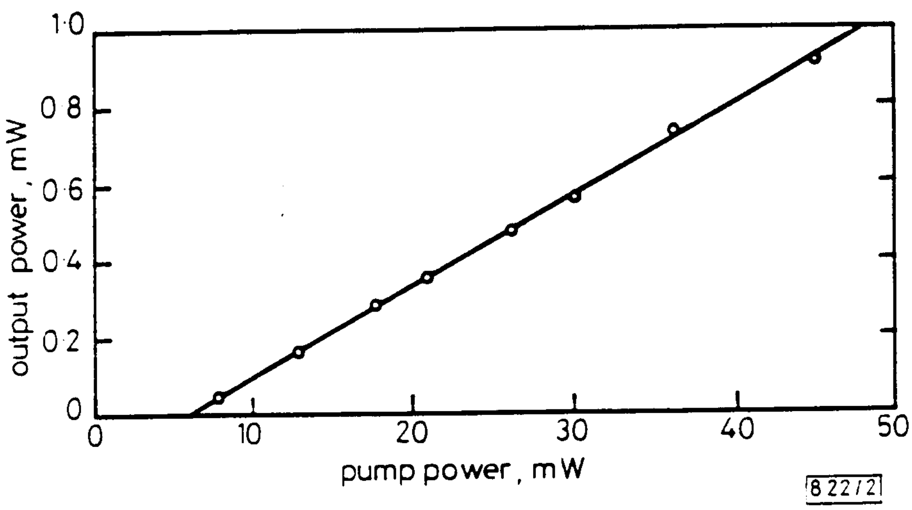


Fig. 2 *Travelling-wave ring laser characteristic*
Threshold 6 mW; Slope efficiency 2·3%

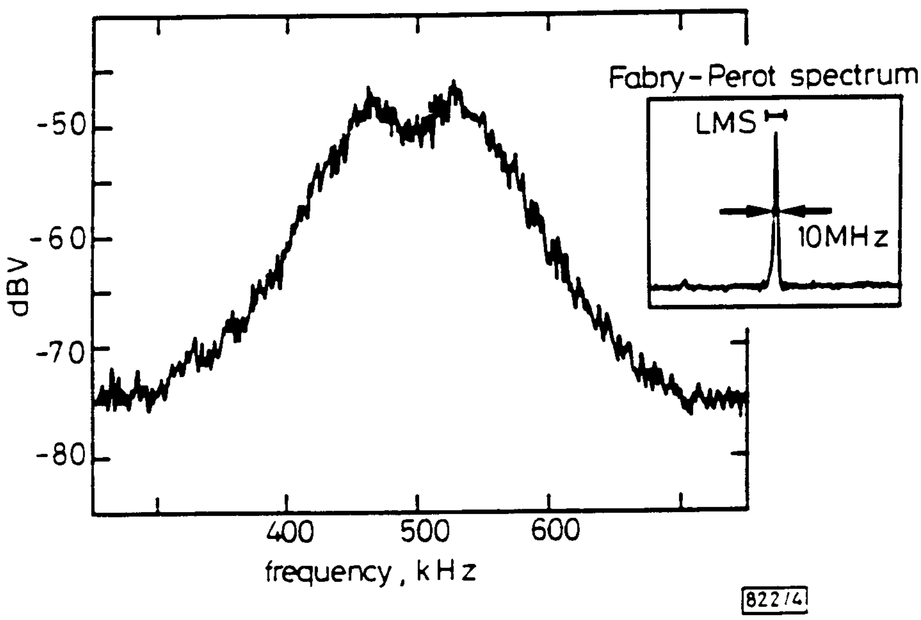


Fig. 4 ***Self heterodyne spectrum***
Inset shows the Fabry–Perot spectrum