RECENT ADVANCES IN ACTIVE FIBRES

W.A. Gambling

Optoelectronics Research Centre,
University of Southampton, United Kingdom

Introduction

Optical fibres have been developed to a high degree of sophistication for long-distance transmission. Compared with coaxial cables which have a bandwidth of 20MHz or so over distances of 3 to 5km, optical fibres can have almost infinite bandwidth and repeater spacings of several hundred kilometres. They are also small, light in weight, flexible and free from electromagnetic interference. It is not surprising, therefore, that optical fibres have already revolutionised telephone and data networks and are being rapidly installed in most countries of the world. Nevertheless, in normal communications terms optical fibre communications is in a very primitive stage of development. The only operation that can be performed is that of transmitting optical information from one point to another. In order to process the information it must be converted back to electrical form and operated on in complex electronic circuits. The information then has to be reconverted to the optical wavelength. Such methods of signal amplification are complex and expensive.

The next stage of optical fibre communication will require fibre components in both passive and active form. Passive components such as couplers, switches and isolators are now becoming available commercially and research leading to active fibre devices is showing considerable promise.

Fibre Lasers

The first major active fibre device was the fibre laser. Laser action is produced by introducing suitable rare-earth ions into the core of a single-mode fibre. When these ions are pumped by an optical source in an absorption band, relaxation occurs rapidly and the ions fall to a metastable energy state. They are then capable of amplifying any spontaneous emission which arises from that state.

Laser action may then be obtained by placing mirrors at each end of the fibre, as shown in Figure 1. The considerable advantages of the fibre configuration are due to the fact that the pump radiation travels along the axis of the fibre and is guided by the core, as is the lasing radiation. There is therefore very efficient coupling between the pump radiation and the ions whilst the pump intensity is very high because of the small core diameter. Pumping efficiencies approaching 100% become possible and slope efficiencies exceeding 60% have been measured, as have threshold pump powers of a few hundred microwatts.

Fibre lasers are small, robust, flexible and give easy access to the laser cavity, thus enabling the operations of Q-switching,

RARE-EARTH-DOPED GUIDED-WAVE LASERS

The Future

- Tunable CW output > 1W
- Q-switched output > 10kW
- Mode-locked pulse duration < 1ps, power > 10kW
- 470nm frequency-doubled output > 100mW
- Intra-cavity non-linear effects in fibres
- Wavelengths 0.9µm to 4µm diode-pumped
- Upconverters into the visible and UV
- New transitions

Table 1

mode-locking and line-narrowing to be carried out. Because of the large fluorescent linewidths large tuning ranges have been reported - up to 70nm in erbium. A new lasing wavelength in the visible region of the spectrum at 651nm has been obtained and others are likely to follow. Figure 2 indicates the various wavelengths, ions and fibres so far reported.

Developments in fibre lasers are occurring rapidly and likely performance achievements over the next five years are listed in Table 1. Fibre lasers have many advantages over diode lasers, as indicated in Table 2, and may well exceed them in performance in all but one aspect. Diode lasers can be directly modulated by an electrical signal whereas the fibre laser requires an external modulator.

An example of the flexibility in cavity design available in the fibre laser is given in Figure 3 where a metal strip is placed alongside the core to provide a high loss to one of the polarisation directions with little loss to the other. Preferred polarisation directions are created by the elliptical core. The output of this laser is linearly polarised. Recently switching between the two polarisation eigenmodes has been demonstrated.

Because of the broad fluorescence width of the laser ions, fibre lasers operate on many longitudinal modes and emit over a range of wavelengths. However, the ease of access to the cavity allows a diffraction grating to be deposited directly onto the core of the fibre. In this way the output can be limited to only a single longitudinal mode thus reducing the linewidth to as little as 1MHz. In a travelling-wave ring configuration the linewidth has been reduced to 60kHz. Grating fibres can be fabricated by polishing the fibre transversely and depositing a grating by photolithography. Alternatively, the grating can be produced by creating a periodic series of defects by optical interferometric techniques, as described below. In principle a distributed feedback fibre laser can be constructed in a localised position in a longer length of fibre without the need for splicing.

Fibre Amplifiers

Probably the most immediate application of rare-earth-doped (RED) fibres will be as fibre amplifiers, which consist of only a short length of RED fibre with optical pumping radiation coupled into the core via a dichroic coupler, see Figure 4. The coupler has a high coupling ratio at the pump wavelength but prevents loss of the signal power. The pump source can be a diode laser of simple construction. It can be seen that the fibre amplifier comprises only three basic components; fibre, coupler and diode laser, so that it is highly reliable, small (10cm to a few metres in length), highly efficient and should eventually be cheap compared with an electronic repeater.

The erbium-doped amplifier operating at 1.55μm has an important future in telecommunications. Gains of up to 40dB have been reported and the noise level is sufficiently low that many can be inserted in tandem along a fibre transmission system operating at large bit rates. In a recent experiment transmission was obtained over 900km of single-mode fibre with 12 fibre amplifiers

SOLID-STATE LASERS V. DIODE-LASERS

- Visible emission possible
- Peak powers > 1kW
- Easy resonator access & complex cavities
- Distributed devices
- Polarisation independent
- Quieter, more stable

Table 2

spaced along it. The bit error rate at a transmission speed of 1.2GHz was 10^{-9} which means that transAtlantic and trans-Pacific, as well as other very long-distance, transmission will soon be possible without any electronic repeaters.

The emission linewidth of the lasing transition is large so that the bandwidth, whilst limited by other factors, is also large. One set of measurements indicates a bandwidth of 20GHz with gains as high as 21dB at 1528nm and 1536nm on either side of the gain peak. The magnitude and phase components of the gain are flat for both AM and FM signals between 130MHz and 15GHz, even with 6dB gain compression at high signal levels.

Table 3 summarises the properties of the erbium fibre amplifier. High efficiency is achieved by adjusting the combination of length and doping concentration so that all of the pump power entering the core is absorbed in the amplifying region of the fibre. So far optical amplifiers are analogue devices and cannot perform digital regeneration but the noise performance is such that perhaps twenty or more can be concatenated whilst still preserving low-distortion/error rates at high bandwidth.

As with other amplifiers the doped fibre amplifier, see Table 4, can be used as a line amplifier, a power amplifier or as a pre-amplifier. Its properties as a line, or signal, amplifier are discussed above. As a power amplifier it is capable of CW output powers exceeding 1W and one of its first applications could well be to amplify the output of a modulated diode laser to form a powerful transmitter. If the diode output is amplified by, say, 20dB then the permitted transmission distance is increased by 100km. Similarly, when placed immediately prior to a detector the receiver sensitivity can be increased by an even greater amount, giving rise to another increase in transmission distance.

The erbium fibre amplifier is very stable because the pumping power is stored in a metastable energy level which acts as a form of reservoir from which energy can be drawn when required. Thus the gain is largely independent of both the wavelength and magnitude of the pumping diode over quite large ranges and when saturation begins to occur the gain only falls by 5dB for an increase in signal power from 10μm to 100μW.

The fibre amplifier is an important new active devices that will have applications in many different situations, ranging from long-distance transmission to local-area networks and sensors.

Second-Harmonic Generation

Glass is a centro-symmetric structure so that the second-harmonic generation coefficient $\chi^{(2)}$ is normally zero and it has not been known to produce second-harmonic energy when an intense optical wave is transmitted through bulk material. However, in single-mode optical fibres a new phenomenon has recently been found to occur. It has been observed that if, for example, a high-power beam from a YAG laser operating at 1.06μm is launched into the core of a single-mode fibre of perhaps a metre in length, then initially no second-harmonic radiation is produced. But after an hour or two a small amount of second-harmonic appears and

WHY ERBIUM FIBRE AMPLIFIERS?

- 1.5µm
- Broadband
- High gain (>30dB)
- Fibre compatible
- Low noise
- Power- or pre- amplifier
- Polarisation independent
- Diode laser pumping

Table 3

gradually increases in intensity. If the input radiation of 1.06μm to the fibre is then removed and later re-applied, the second-harmonic signal appears immediately although at a somewhat lower level than before. The effect is permanent so that the properties of the glass in the core of the fibre have been changed and the core glass exhibits a finite $\chi^{(2)}$. It seems that some kind of defect structure is created in the glass but the precise nature of the changes are not yet fully understood.

An additional effect can be produced by applying a large transverse electric field to the core, in fibres of the composite metal/glass structure illustrated in Figure 5. The first has two integral longitudinal electrodes located on opposite sides of the circular core whilst the other is a D-shaped fibre with one internal electrode close the elliptical core and a metal layer applied to the flat surface of the fibre. In either case the separation between the longitudinal metal electrodes may be varied from 10μm to 30μm. If a potential of a few kilovolts is applied to the electrodes, the electric field across the core can be as high as 800V/μm. The fundamental glass structure is then modified and both second-harmonic generation and a permanent Pockels effect are induced. It is likely that an effective $\chi^{(2)}$ is created by the alignment of existing defect centres formed during the fabrication process by the applied electric (or poling) field. The creation of a permanent $\chi^{(2)}$ can be greatly enhanced by launching blue light into the fibre, or by illuminating with UV light from the side during the poling process. The short wavelength radiation induces a large number of defects (or colour centres) via single photon, or two photon, absorption processes.

With the above forms of second-harmonic generation the phase constants of the fundamental and second-harmonic waves are not normally equal because of the fibre dispersion. The effective (coherent) length is limited to a few tens of microns. The harmonic conversion efficiency can, therefore, be increased by several orders of magnitude if phase-matching of the two waves is achieved. Several phase-matching techniques have been developed.

The first comprises modal phase-matching. By appropriate fibre design the phase constants of the fundamental and second-harmonic waves can be equalised if they propagate in two suitable higher-order modes. A relatively long coherent length is thereby produced but the design tolerance of this method is small.

The second technique involves "seeding" a polarisation-preserving fibre. Both the fundamental beam and its second-harmonic (obtained externally) are launched into one of the principal axes of a polarisation-preserving fibre for about 10 minutes. A $\chi^{(2)}$ grating is created by interference between the two waves.

The third method uses optical excitation poling. Blue light (either CW or pulsed) is launched into a fibre during the electric-field poling process. The fibre is designed to be single-moded at the fundamental wave (at around 1μm) and slightly multi-moded at the blue (e.g. 488nm from an argon-ion laser) wavelength. An interference pattern is formed between the modes

APPLICATIONS OF OPTICAL AMPLIFIERS

Power Amplifier	Line Amplifier	Pre-Amplifier
● Boosts source power	● Low Noise	● Low Noise
Telecoms Non-linear switching PS pulses	Telecoms repeaters	Improved detection High bit-rates

Table 4

(at 488nm) resulting in a stationary, periodic, intensity distribution axially along the fibre core. The blue light causes defects to be created at the antinodes and the dc electric poling field aligns the defects to form a $\chi^{(2)}$ grating structure corresponding to the blue light distribution.

Gratings can also be written by transverse illumination by interfering beams or by the application of a periodic electric-field.

The creation of defects may have considerable potential applications as the following two examples show.

In the first, Figure 6, a high-power input at 1.06μm to a conventional single-mode fibre creates defects after a period of several hours and the second-harmonic intensity is initiated and increases. By appropriate fibre design the phase constants of the fundamental and second-harmonic waves can be equalised thus creating a standing optical wave and thus a periodic series of defects - in other words a $\chi^{(2)}$ diffraction grating, Figure 7. The second-harmonic generation efficiency is thereby increased and values as high as 13% have been achieved, with a peak input power of 1kW.

In the second example blue light is launched into a slightly multimoded "D" fibre, of 30cm length, to which a d.c. electric field of 140V/μm is applied. The cut-off wavelengths of the two orthogonally-polarised modes of the elliptical core were 1.12μm and 1.17μm. Blue light at a wavelength of 488nm was launched equally into each of these modes of the fibre, resulting in an interference pattern between two modes and a stationary periodic intensity distribution axially along the fibre core. Over a period of 10 minutes the 40mW of power from the argon laser caused defects to be created at the antinodes. The d.c. electrical poling field aligned the defects to form a $\chi^{(2)}$ grating structure corresponding to the 488nm intensity distribution. Such mode interference gratings (MIG) remain permanently in the fibre after the 488nm radiation and the poling field are switched off.

When infra-red light, of wavelength typically 1.0μm to 1.2μm, is then launched into the fibre an efficient generation of its second-harmonic may be obtained by a correct choice of modes for the fundamental and its harmonic. Phase-matching of the fundamental and second-harmonic can take place over a wide range of infra-red design wavelengths by an appropriate choice of blue excitation wavelength and fibre parameters. In this example the second-harmonic conversion efficiency was 1% but increases of between one and two orders of magnitude should be possible. Such gratings can be erased by blue light in the absence of the poling field and can easily be re-written. Gratings can also be written by transverse illumination by interfering beams.

Tunable Fibre Lasers

It is clear that techniques are now available, and there are others in addition to the two examples given above, for writing gratings of pre-determined pitch in an axial direction along the

WORLD-CLASS RESULTS FORECAST

- Tunable, fs-pulse, all-guided-wave laser emitting > 10kW peak power at 1.55μm
- New laser transitions
- High-power diode-pumped solid-state guided-wave sources emitting > 1W c.w.
- Tunable up-converter guided-wave lasers emitting in the visible and blue regions. Output power > 100mW.
- Low-noise c.w. & fs-pulse amplifiers for pre-, line and power amplification. Output power > 1W c.w.
- All-optical switching & new non-linear effects
- Distributed acoustic, intruder, radiation & temperature sensors

Table 5

core of an optical fibre. There are many potential applications of such gratings in both passive and active fibre devices. It is now possible to make a distributed feedback fibre laser of stable, and very narrow, linewidth. Fibre lasers with discrete grating reflectors operating on a single longitudinal, and single transverse, mode have already been mentioned. Passive devices could include in-line narrow-band filters and resonators, including Fabry-Perot structures, all designed for the required wavelength.

Another application of considerable potential importance is to parametric amplifiers and oscillators via the mechanism of three-wave mixing which has recently been demonstrated. Thus new coherent optical wavelengths can be generated at any selected wavelength, with the possibility of tunable operation. The realisation of such devices is only a matter of time.

Conclusions

The revolution in telecommunications brought about by the advent of conventional single-mode optical fibres is only the first stage in their exploitation. The second stage, namely their application to passive components and optical sensors, is proceeding steadily but not very rapidly. The third stage, involving the creation of a new range of active devices, is upon us and is advancing very rapidly indeed. Some predictions of performances likely to be achieved within the next five years are contained in Table 5. Compared with what was thought possible only two years ago these are remarkable indeed.

Active fibre devices can be designed and fabricated for specific applications and wavelengths. Many new devices, sources and sensors are now possible and it is expected that the range will be extended by the introduction of new fibres based on new materials, some of which perhaps can only be created in fibre form. There will be parallel developments in similar planar optical devices as fibre fabrication techniques are adapted to planar technology. The drive towards creating new devices, particularly those involving non-linear optical effects, will also shed light on many fundamental optical and materials properties. The next few years will be very fruitful.

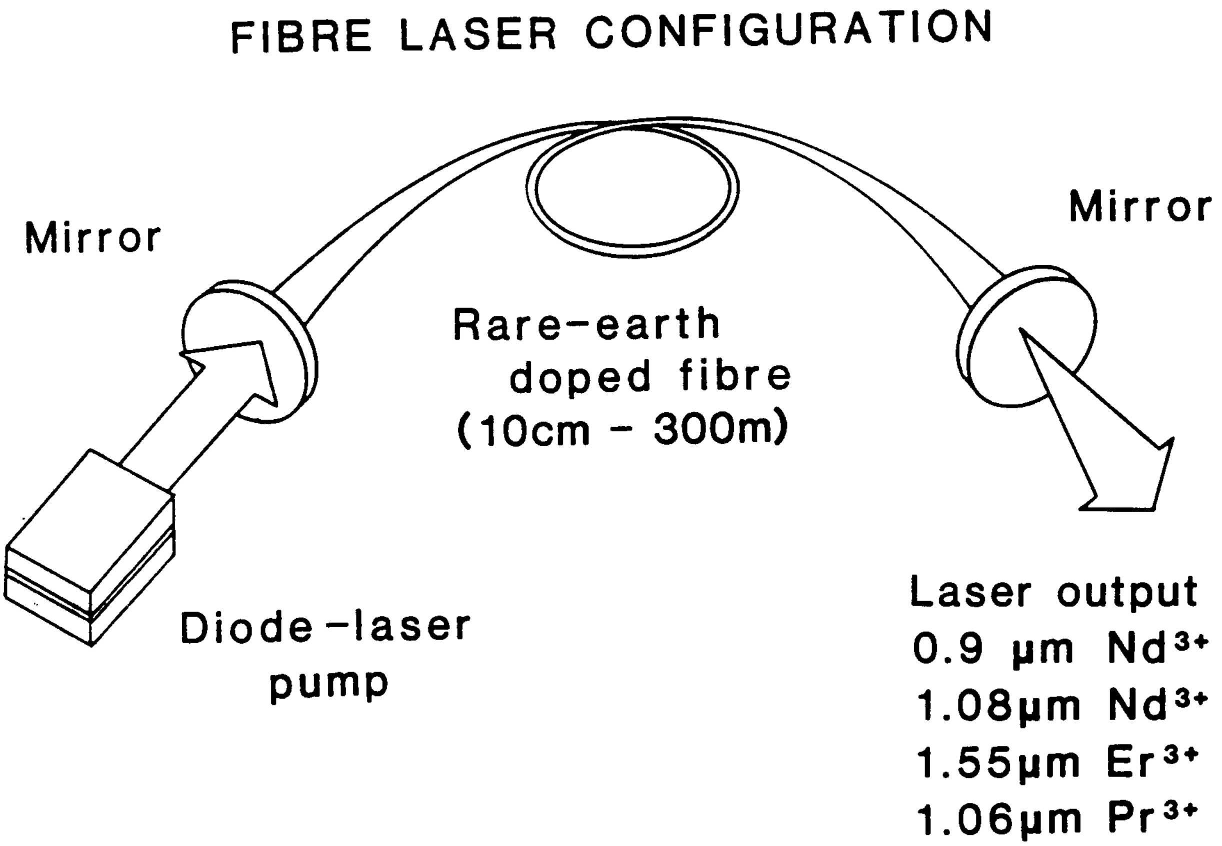

FIBRE LASER CONFIGURATION
Mirror
Mirror
Rare-earth doped fibre (10cm - 300m)
Diode-laser pump
Laser output
0.9 µm Nd3+
1.08µm Nd3+
1.55µm Er3+
1.06µm Pr3+

Figure 1

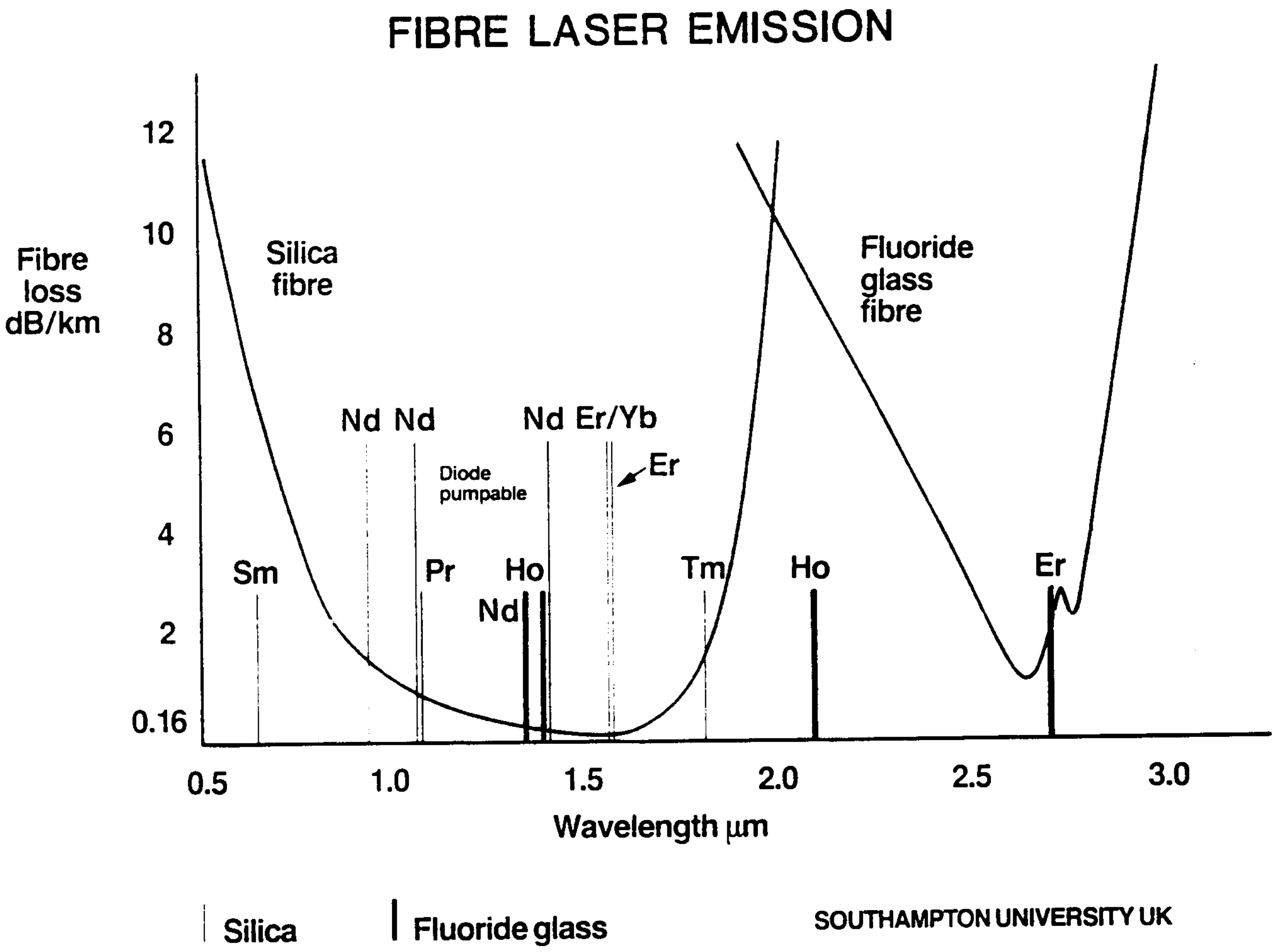
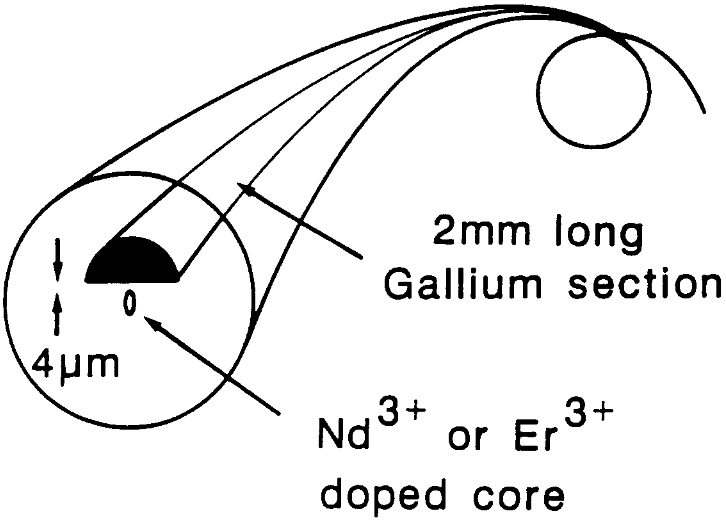

FIBRE LASER EMISSION
Fibre loss dB/km
12
10
8
6
4
2
0.16
Silica fibre
Fluoride glass fibre
Sm
Nd
Nd
Diode pumpable
Pr
Ho
Nd
Nd
Er/Yb
Er
Tm
Ho
Er
0.5
1.0
1.5
2.0
2.5
3.0
Wavelength µm
Silica
Fluoride glass
SOUTHAMPTON UNIVERSITY UK

Figure 2

POLARISED FIBRE LASERS
with integral fibre polariser



	Polarised Output	Extinction ratio
Nd^{3+} (1.09μm)	20mW	35dB
Er^{3+} (1.55μm)	1.2mW	22dB

Figure 3

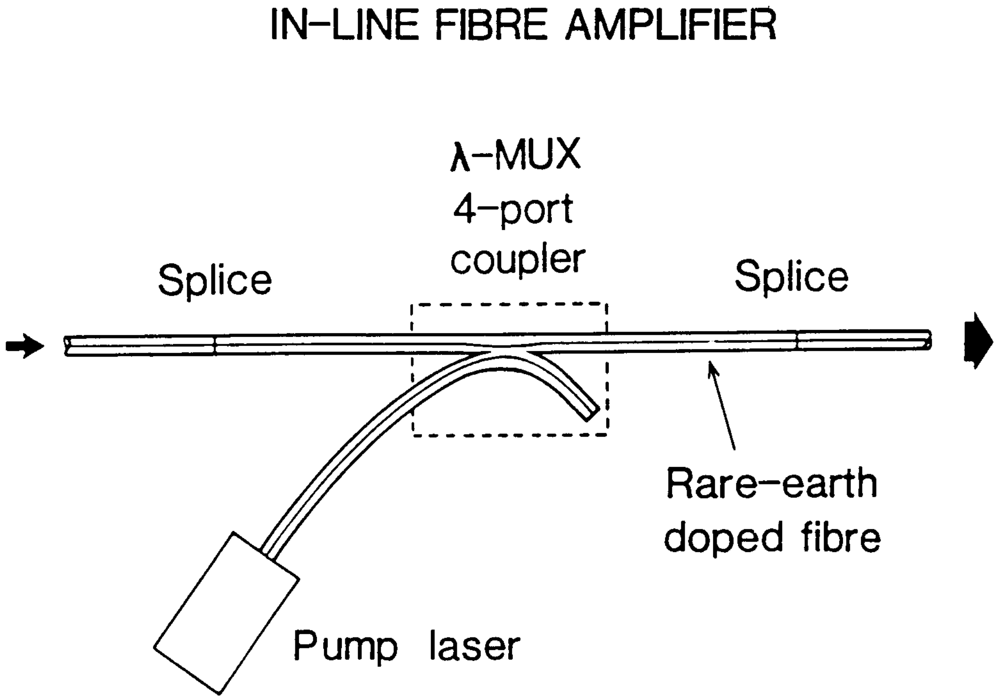
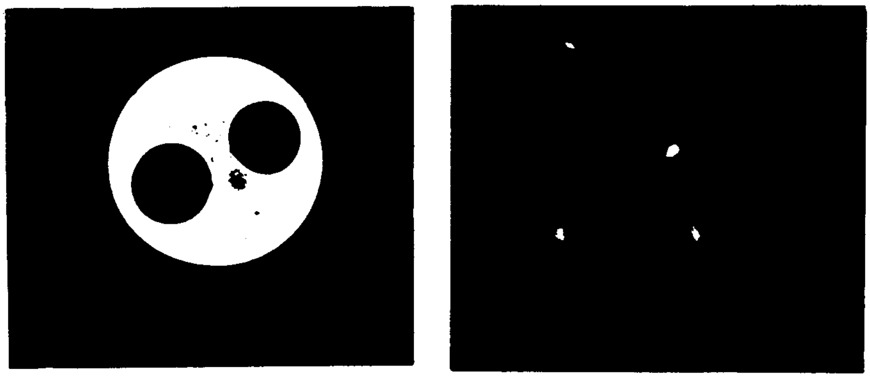

IN-LINE FIBRE AMPLIFIER
λ-MUX
4-port
coupler
Splice
Splice
Rare-earth
doped fibre
Pump laser

Figure 4

FIBRES WITH INTEGRAL ELECTRODES



Electrode
separation: **15µm** **22µm**

Figure 5

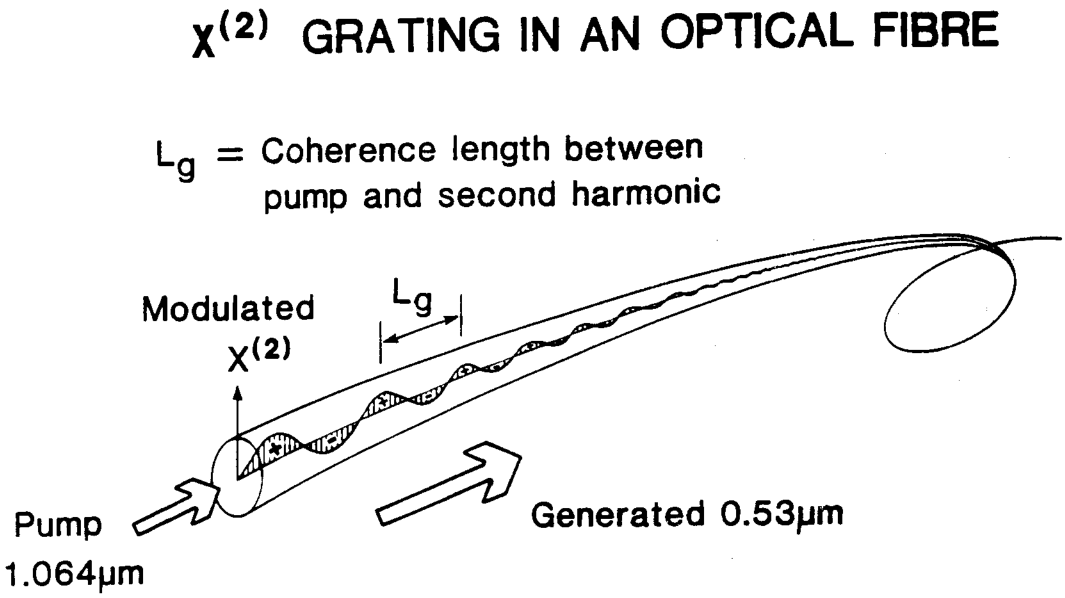
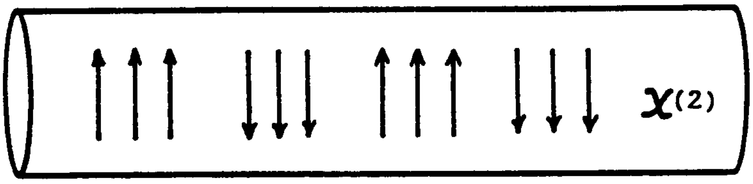

$\chi^{(2)}$ GRATING IN AN OPTICAL FIBRE
L_g = Coherence length between pump and second harmonic
Modulated $\chi^{(2)}$
L_g
+
−
Pump 1.064µm
Generated 0.53µm

Figure 6

SECOND-HARMONIC GENERATION IN FIBRES

- Create defects in core with blue light
- Align defects with electric field to give $\chi^{(2)}$
- Phase match with periodic structure or 2 modes



Pump/SHG
Coherence
Length

13% conversion efficiency obtained

Figure 7