EPS Amsterdam Sept 1990.
(European Physical Society)

Fibre Lasers and Amplifiers

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Abstract

A brief review is given of the current status of research in the field of rare-earth doped fibre lasers and amplifiers. The merits of making such devices in fibre form are discussed, together with their potential applications.

Introduction

What can you do with a laser?. Use it to separate atomic isotopes; measure the distance to the moon; record music; cut steel; fuse nucleii: the list grows longer every day. Lasers have changed many branches of science and introduced new ones. Of course, lasers are also interesting in their own right. They are systems driven far from thermal equilibrium so allowing us to test theories under extreme conditions. Increasingly they are also found in numerous everyday applications such as manufacturing, printing, communications etc... The exploitation of lasers in this way requires them to be both cheap and compact. This is why the semiconductor laser has been so successful, combining a compact design with an already existing manufacturing technology, that of microelectronics.

We describe in this paper another class of laser that is also compact and potentialy cheap, with a ready made manufacturing process already established - fibre lasers. They may in fact be described as second generation lasers since their input energy (known as the pump energy) is derived from another laser - often a semiconductor laser. Fibre lasers form part of a new family of laser pumped miniature solid state lasers that are now becoming increasingly important in both science and technology.

Basics

In principle and sometimes in practice, the fibre laser is very simple [1-3]. A gain medium is formed by doping the core of an optical fibre with rare-earth ions. Pump light is introduced at one end of the fibre to excite the ions, so enabling the creation of a population inversion. Mirrors at either end of the fibre ensure that amplified spontaneous emission is built up resonantly until laser oscillation occurs. One piece of doped fibre, two mirrors, one pump source and thats it

- simple, fig 1. Indeed, dielectric mirrors have been direct coated onto the ends of a piece of doped fibre which in turn has been pigtailed onto a laser diode, thus proving the simplicity [4].

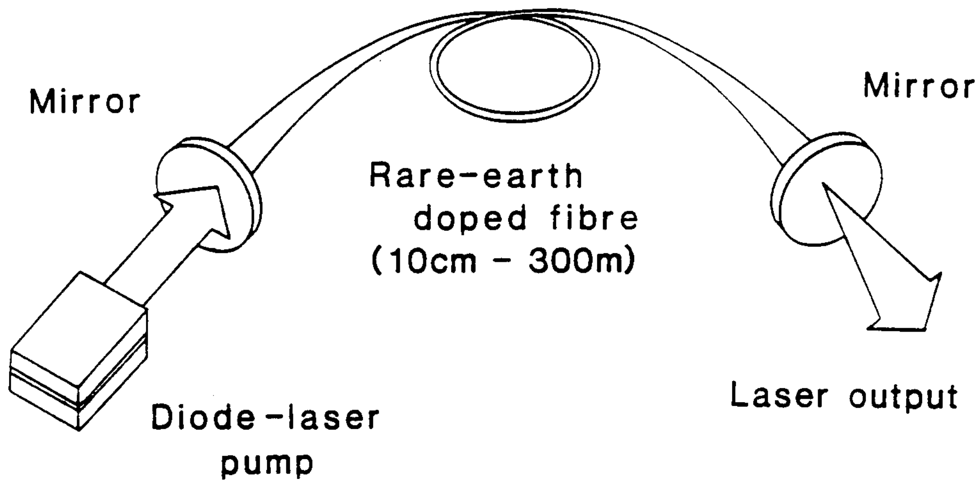

Figure 1 Scematic of fibre laser

As it stands, this set-up does not allow the full potential of fibre lasers to be exploited - a few more components are required and we will discuss these later. The fibre amplifier however is this simple and is becoming an essentail component in modern commmunications so that we will discuss this first before going on to look at lasers. Before looking at either let us examine some of the physics common to both.

Principles

Fibre lasers and amplifiers combine a gain medium with the geometry of an optical waveguide. The waveguide environment immediately provides some advantages over comparable bulk devices. Perhaps the most important of these is the optical intensity: a $10mW$ pump source produces an intensity of $3 \times 10^8\ W/m^2$ in a typical fibre core. The saturation pump power, P_{sat}, required to reach 50% inversion is,

$$P_{sat} = \frac{h\nu A}{\sigma\tau}$$

$h\nu$ is the photon energy (typ $10^{-19} J$)
A is the fibre core area (typ $10^{-11} m^2$)
σ is the pump absorption cross section (typ $10^{-24} m^2$)
τ is the fluorescent decay time (typ $10^{-4} s$)

so that saturation powers are typicaly 10 mW. A low power pump source, eg the laser from a compact disc player, may thus be used to pump a fibre laser. The geometry of the fibre (ie high surface area to volume ratio) also means that the thermal problems that plauge bulk lasers are largely elliminated. The long interaction length between dopant and pump field, brought about by the waveguide nature of the fibre, means that high single pass gains can be achieved. This is particularly important for the fibre amplifier.

Because of the advantages mentioned above, CW laser action can be achieved in three level laser systems - previously pulsed operation was the norm. Further, many of the less common transitions can be made to lase. By using a fibre that is single mode at the lasing wavelength, lasing in a single TEM_{00} transverse mode is assured - important in many optical applications. If the fibre is also single mode at the pump wavelength then good overlap is achieved between pump and dopant - this can lead to very efficient operation. Single longitudinal mode operation (and therfore narrow linewidth) is another matter and we will come back to it later. First we will examine the fibre amplifier.

The fibre amplifier

Now on the verge of production after only a few years since initial demonstration [5,6], the erbium doped fibre amplifier is a major success. Again, it is a very simple device that also provides many advantages over possible alternatives such as the semiconductor optical amplifier. The amplifier is shown schematicaly in fig 2.

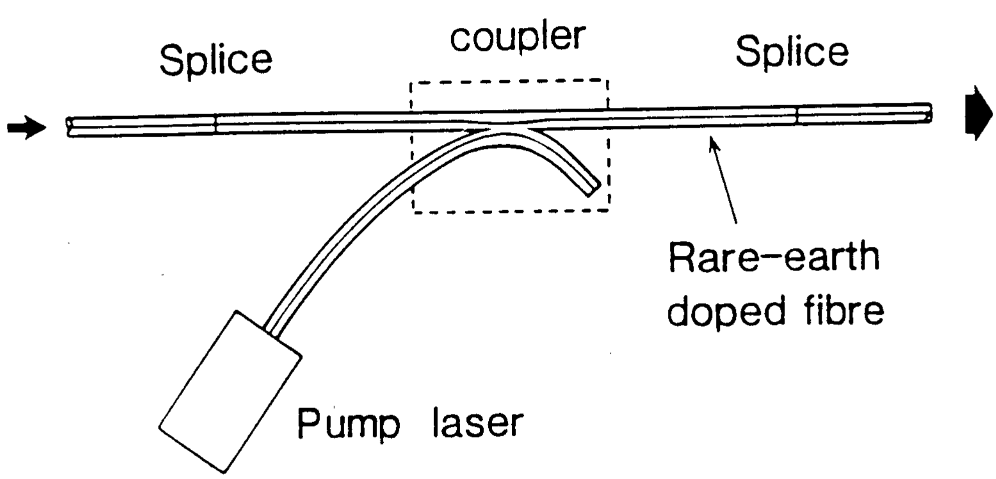

Figure 2 Schamatic of the fibre amplifier

A laser diode provides the pump light and this reaches the doped section via a special fibre coupler. The coupler combines pump and signal light launched in opposite arms of the coupler so that they emerge from the same exit arm. Such couplers are now standard and present no problem. Of course, the amplifier is fibre compatable and may be directly spliced into a network with very low insertion loss.

Erbium (Er^{3+}) is used as the dopant for this application since it has a fluorescent transition based at $1.53\mu m$ - coincidentaly the absorption minimum for silica fibres. The amplifier is thus ideally suited as a repeater for long distance communications. Gains as high as $45dB$ have been demonstrated thus allowing repeaters to be spaced some considerable distance apart. Saturation of the amplifier due to amplified spontaneous emission prevents higher gain. In practice an amplifier used as a repeater may operate at a lower gain of $\sim 20dB$: if very high gains are used lasing will eventualy result due to feedback from back scatter in the communications link. Recently a demonstration of coherent communication took place over 2000km using twenty five erbium fibre amplifiers [7].

After initial demonstration, considerable development has taken place. Er^{3+} has many absorption bands of which the one centered at $0.8\mu m$ overlaps best with that of available laser diodes. Unfortunately however there is also an absorption at $0.8\mu m$ from the metastable level - excited state absorption [8], and this considerably reduces the efficiency of the amplifier. An interesting physical solution is to co-dope the Er^{3+} with Yb^{3+}. The Yb^{3+} can then be pumped at a wavelength that does not cause excited state absorption, the energy is then transferred non-radiatively to the erbium system, fig 3. This energy transfer process is not very efficient when the dopants are held in silica based glass. Communications fibres are based on silica so that for compatability so should the amplifier. As a result, instead of co-doping with Yb^{3+} and using $\sim 800nm$, a different absorption band is used. Two are possible, either $0.98\mu m$, or in-band at $1.49\mu m$. Because of the importance of the amplifier, semiconductor lasers have been developed at both of these wavelengths.

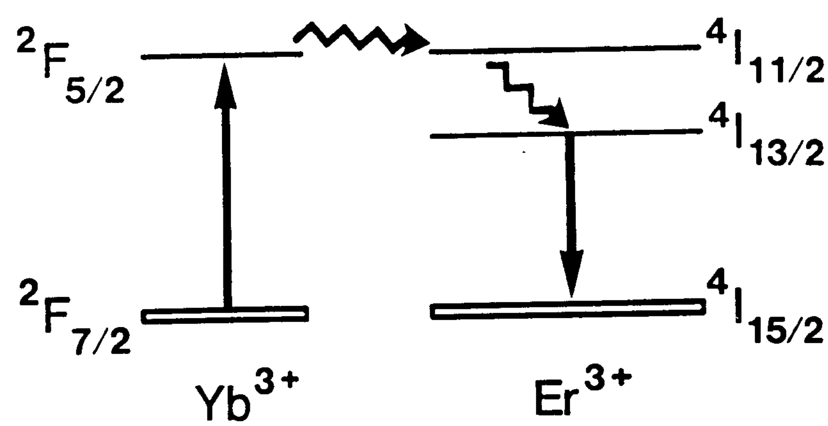

Figure 3 Energy levels involved in $Yb^{3+} - Er^{3+}$ energy transfer

As mentioned above, for compatability with communications links the amplifier is made from silica fibre. However, pure silica is not a particularly good host for Er^{3+}. Fortunatly the host can be modified by the introduction of such compounds as Al_2O_3. This particular compound broadens the transition, thus flatening the gain spectrum of the amplifier. This then has the advantage that in a communications link, more channels may be amplified simultaneously.

A lot of materials work has been carried out on this and related matters, such as the effect of host on excited state absorption. These together with the fabrication process are described elsewhere in this volume and in refs [9-11]. To be specific, the advantages offered by the erbium doped fibre amplifier are;-

- They operate at around 1.5μm and are thus well suited to optical communications.
- They are low power devices and can be pumped by laser diodes, this makes them practical.
- They may provide high gain.
- They are polarization insensitive.
- They are low noise devices.
- Due to the large degree of energy storage and long fluorescent lifetime they demonstrate both low distortion and low crosstalk.

In addition to their rather obvious use as a repeater in a comunications link, ther are other important ways of using the amplifier. One of these is as a pre- or power amplifier. This is likely to be important in such applications as cable TV. We can imagine the main signal needing to be split a thousand ways to be sent from a local distribution point to individual homes, fig 4. By using a 30dB amplifier before the splitting takes place the signal level launched into the individual fibres can be maintained at the initial level.

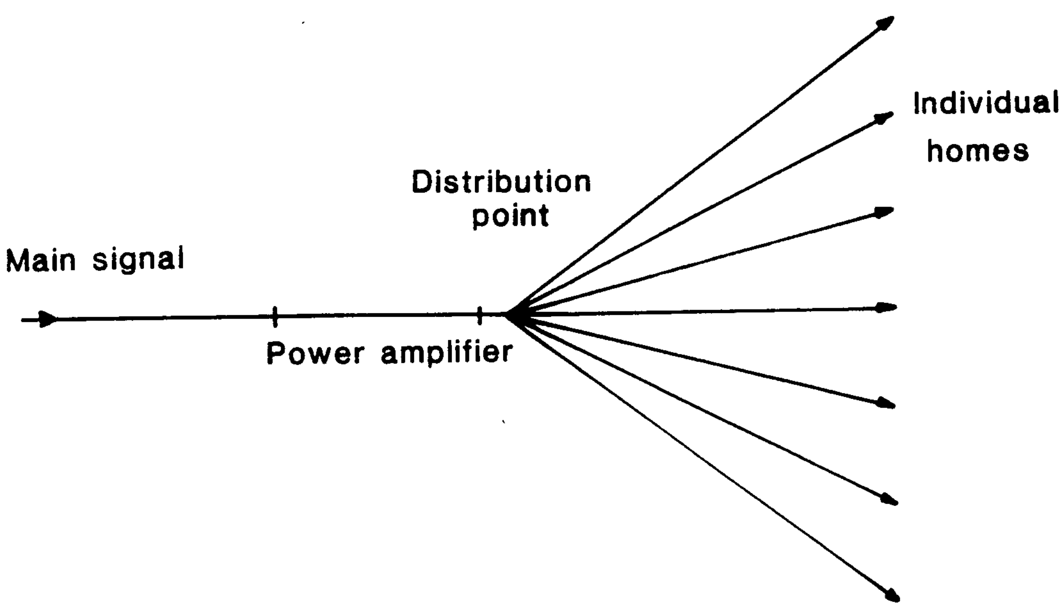

Figure 4 Doped fibre used as a power amplifier

The high saturated output powers possible from the fibre amplifier make it ideal for this use. (Saturation of the output power occurs because an increasing proportion of pump power is converted to amplified spontaneous emission as the amplifier is pumped harder.)

Fibre Lasers

Add feedback to the fibre amplifier and we have a fibre laser. Let us look at some specific examples. The Nd^{3+} system operating at $\sim 1.08\mu m$ demonstrates well the low threshold nature of the fibre laser, as shown in fig 5. In fact, by careful choice of output coupling the threshold can be reduced to below $100\mu W$ of pump power [12]. The 3-level erbium fibre is also easy to operate - even with a diode pump source. The efficiency of these lasers can be very high, often limited to the difference in pump and laser photon energies. Many different fibre lasers have now been operated with very high efficiency and at many different wavelengths in the visible and near infrared [4,13-15]. Although still mainly at a research stage, many potential applications exist for fibre lasers, these range from magnetometers [16] to laser cooling [17].

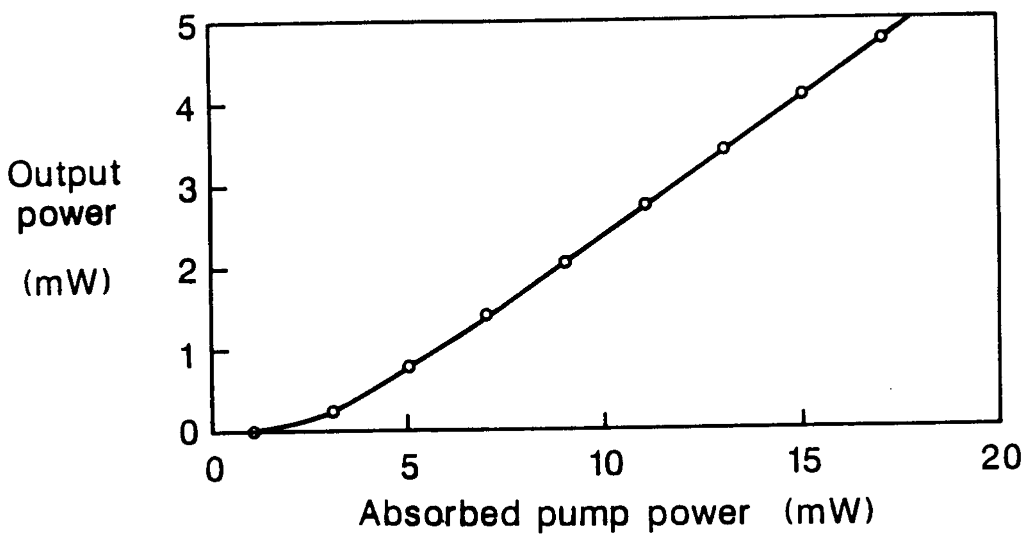

Figure 5 Neodymium fibre laser characteristic

With no wavelength selection fibre lasers typicaly operate with a spectral width of $1 - 15nm$, containing many thousands of cavity modes. There are many applications where narrow linewidth operation is desirable - for example as a source for coherent communications. This requirement can be met with fibre lasers provided they are made to operate in a single longitudinal mode. Most of the standard line narrowing techniques can be used to some effect, such as distributed bragg reflection from a grating [18]. So far, gratings have been produced by etching a holographic pattern close to the fibre core. It is hoped that photorefractive gratings might be used for this, in which case the polishing and etching steps of the standard process could be dispensed with [19].

The problem in line narrowing a fiber laser differs from that applicable to a semiconductor laser. The later have short cavities so that the resulting cavity modes are well spaced and thus easily selected. The problem is then one of narrowing the individual mode. In the case of the fibre laser the cavities are normaly much longer so that cavity modes are closely spaced.

Line narrowing thus depends on selecting just one of these modes. The fact that many modes oscillate when no wavelength selection is present can be attributed to spatial hole burning. One approach which overcomes spatial hole burning is to make a travelling wave laser, linewidths of order $100kHz$ have been achieved in this way [20]. This is easily formed in fibre by making a ring laser - fig 6 based on a fibre coupler. An isolator is required in the cavity to prevent oscillation occuring in both directions and thus re-introducing the problem of spatial hole burning.

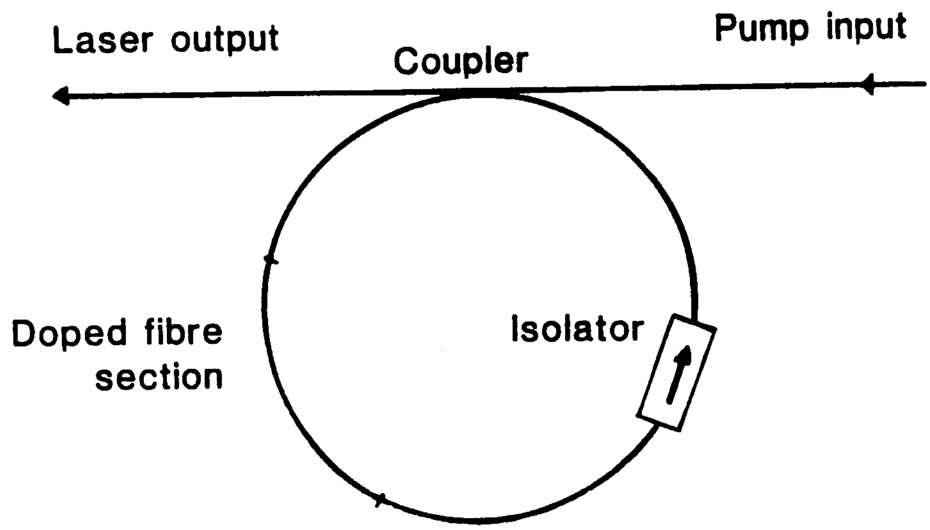

Figure 6 Fibre ring laser

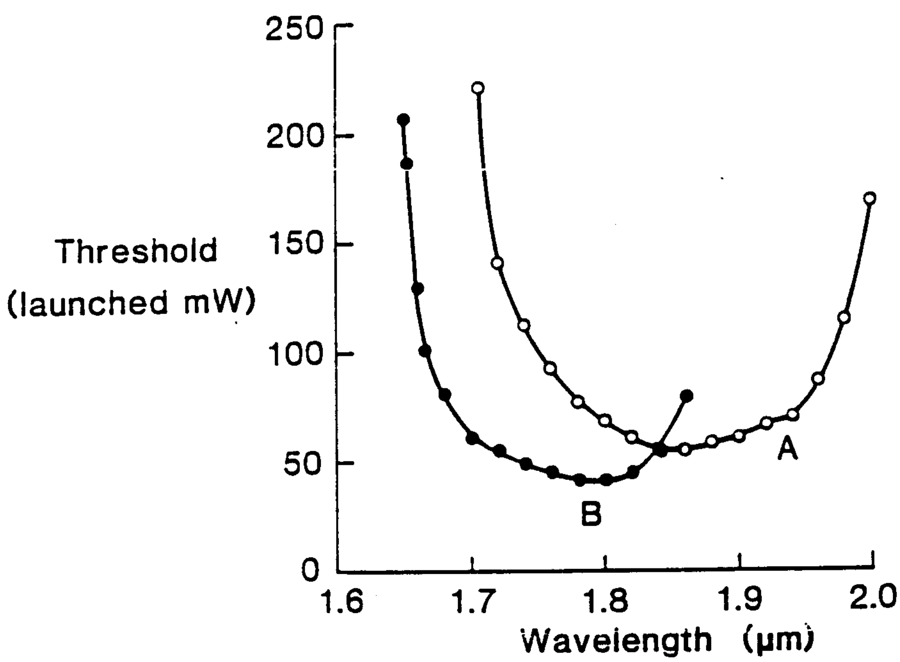

Figure 7 Tuning of Tm^{3+} fibre lasers. A is $Al_2O_3 - SiO_2$ fibre, B $GeO_2 - SiO_2$

Due to the glass nature of the silica host many of the rare-earth transitions are very broad. This arises both from inhomogeneous broadening of the transition and removal of level degeneracy by a significant amount of stark splitting. Consequently many fibre lasers may be tuned over an extensive range [15,22]. Fig 7 shows the tuning range of two Tm^{3+} lasers. Although most experements have used bulk tuning methods such as diffraction gratings or birefringent filters, the possibilty exists to use photorefractive gratings written directly into the fibre. This would provide a form of distributed feedback and might perhaps be tuned by stretching the fibre.

Fibre lasers are generally thought of as low power devices, largely because of their low operating thresholds. However, there is no reason why they sould not be operated at high power and indeed this is now being done. Output powers in excess of $1W$ have now been obtained from several differen lasers [13], including over $5W$ from an erbium laser [22]. Output has so far been limited by the available pump power. Thermal problems in the fibre have not yet been encountered although damage to the dielectric mirrors has. By using multimode fibre, the intensity on the mirror can be reduced thus allowing a greater pump power level to be used. The increase in threshold that results from the use of a larger core area is insignificant since at high powers these lasers are operated a long way above threshold.

The fibre laser will find many uses once narrow linewidth *and* tunable operation can be obtained in one simple device - a not unreasonable expectation. In particular such a laser will be a useful source for spectroscopy and optical sensors. Electronic tunability has recently been demonstrated [23] but much more work is required.

Pulsed fibre lasers

In addition to CW operation as discussed above, it is also easy to build fibre lasers that operate in pulsed mode, either Q-switched and/or mode-locked. In general this requires the addition of extra components in the laser cavity. Due to the high gain of most fibre lasers the extra loss so induced can easily be tollererated; however, all fibre components are now being developed for this application.

Although many methods exist for Q-switching [24] it is most commonly achieved using an acousto-optic modulator, fig 8. With the modulator on there is no feedback and pump energy is stored by the population inversion. By turning the modulator off, feedback commences and oscillation takes place. The population inversion is rapidly depleted by this oscilation so that lasing rapidly becomes impossible - a pulse is thus produced. The modulator is now turned on again and energy stored for the next pulse. Q-switched fibre lasers could be used as sources in sensors, medical applications and rangefinding. Er^{3+} is particularly suited to rangefinding because operation at $1.5\mu m$ is to some extent eye-safe.

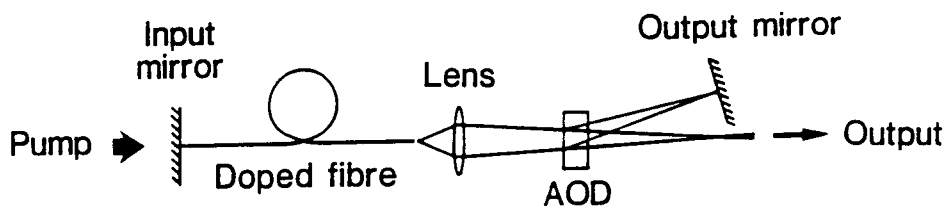

Figure 8 Experimental arrangement for Q-switching with a modulator (AOD)

Mode-locking can be very simple and very effective, the large gain bandwidth of the fibre laser means that very short pulses may be produced - a few *ps* have been achieved [25,26]. The potential exists for making a simple mode-locked source that is entirely passive in operation by employing the additive pulse mode-locking technique. The required arrangement is shown in fig 9.

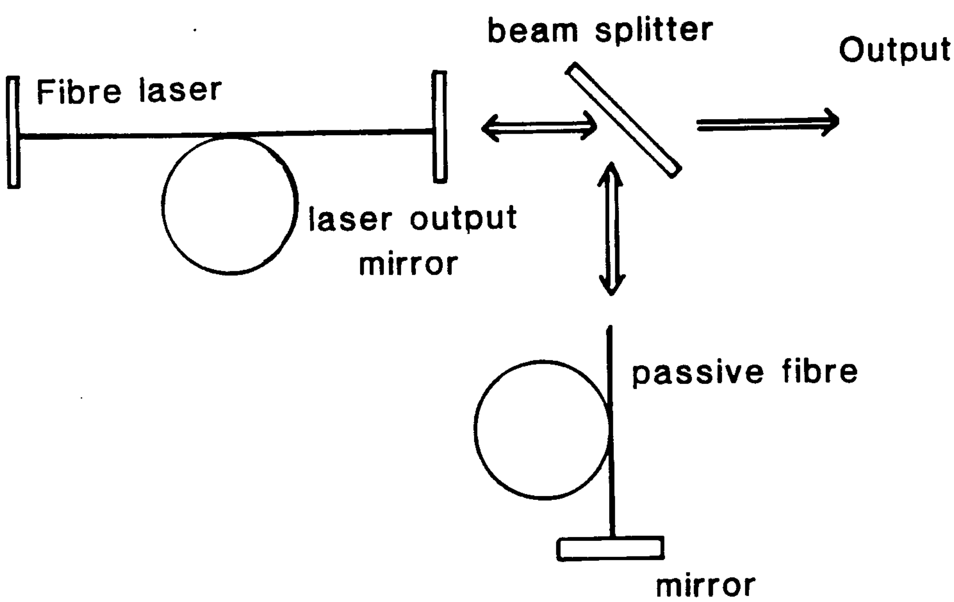

Figure 9 Additive pulse mode-locking

Let us consider a pulse hitting the output mirror of the laser. Part of it is reflected and part transmitted. Some of the transmitted part is directed down a length of passive fibre, is reflected at the far end and is eventually fed back into the laser. If the path lengths are chosen carefully the returning pulse will arrive at the output mirror at the same time as the remaining fraction of the initial pulse has made a round trip of the laser cavity. Both the pulse in the laser and that in the passive fibre suffer from self-phase modulation. By this we mean that the index that the pulse sees on propagating down the fibre depends on the optical intensity. Consequently, the phase change to a given part of the pulse depends on the intensity at that part of the pulse. Both pulses are thus chirped, though to differing degrees. As a result the two pulses interfere constructively only at the centre of the pulse, thus reducing it's temporal width. Although the effect is only small it is additive so that significant pulse compression can take place. By adding components to control the degree of chirping it has recently been possible to obtain pulses as short as $125 fs$ [27].

Upconversion Lasers

By upconversion we mean a laser that emits at a shorter wavelength than that at which it is pumped. These are most commonly based on two or three stage photon absorption. Fibres provide an ideal geometry for upconversion, based again on the high optical intensities and long interaction lengths. Rare-earth doped materials can be efficient for upconversion provided suitable metastable, intermediate levels are available to act as a storage resevoir for the pump energy. Rare earth doped fibres are thus good candidates for solid state upconversion lasers and if they can be pumped by diode lasers, will allow the development of compcat visible sources.

Refering to the diagram, fig 10, an initial pump photon can excite an ion to an intermediate metastable level. Absorption of a further photon, ie excited state absorption, may then raise the ion to a higher metastable level from which lasing may take place. This level might also be reached by energy transfer but we will not discuss that here.

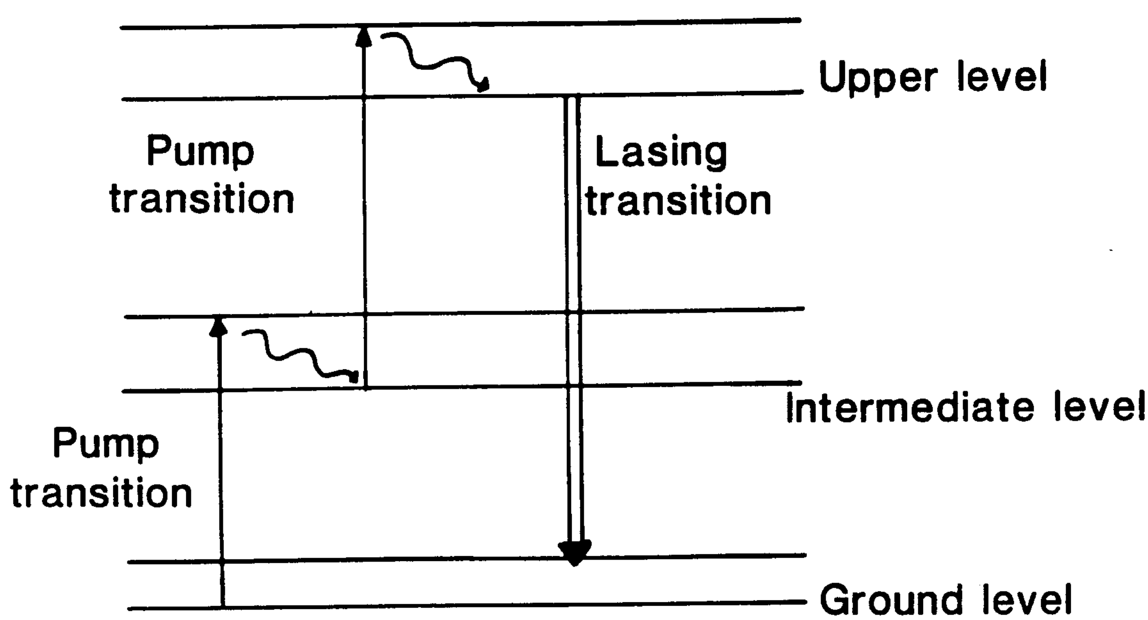

Figure 10 Upconversion energy level diagram

To obtain a significant poulation inversion in the upper metastable level we require the intermedite level to be heavily populated, ie we want the ground state absorption to be well saturated. This may easily be achieved in fibres because, as explained earlier, the saturation pump power is very low. So, providing that siutable pump wavelengths can be found, a diode pumped upconversion fibre laser is not unrealistic.

Room temperature operation of upconversion fibre lasers has now been reported [28]. Holmium (Ho^{3+}) was pumped in the red at $647nm$ and lasing occured in the green at $550nm$ (a two visible colour visible source can thus be produced). We should note that laser diodes are now available that operate in the red, and thus may become suitable for pumping Ho^{3+}. An upconversion efficiency of 12% was obtained so that for $300mW$ of pump power, $10mW$ of green light was produced. We should note that upconversion lasers have to-date been based on fluorozirconate fibres. Such materials have low phonon energies so that phonon damping of some of the rare-earth transitions is less pronounced than in silica.

Summary

This review has of necessity been brief and incomplete. We could for instance have discussed superfluorescent sources, lasing at $1.3\mu m$ or cladding pumping. These and other topics may be found in the review by Urquhart [29] and references therin.

Acknowledgements

The author is indebted to many collegues within both the Optical fibre and Laser physics groups at Southampton University who carried out much of the above work.

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