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FIBRE LASERS

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INTRODUCTION

The first fibre laser, described by Snitzer[1], was also the first glass laser. The glass fibre, doped with trivalent neodymium ions (Nd^{3+}) was transversely pumped by a flash lamp. The fibre geometry was chosen to exploit the brightness enhancement of pump light in the core after passing through the clear cladding, and also to provide a structure which was more forgiving of the optical inhomogeneities of the doped glass[2]. These early fibres clearly demonstrated the capability for very high gain, with 47dB measured[3] at 1.063μm, even if the transverse pumping geometry was of very low efficiency.

The next major development was the demonstration that longitudinal pumping, using a laser as the pump source and end-launching the pump light into the doped core, gave greatly reduced threshold, and high efficiency[4]. In this way cw operation was easily obtained and it was recognised that pumping of Nd-doped fibre using laser diodes operating at ~0.8μm would provide a simple and practical form of fibre laser.

The third major development, coming 12 years later, and which initiated an enormous growth of interest in fibre lasers and amplifiers, was the demonstration of lasing and amplification in rare-earth-doped monomode silica fibres[5,6]. The erbium-doped fibre amplifier (EDFA) has been the main reason for this explositon of interest. Its success is based on the fact that erbium-doped silica fibre offers an amplifying transition[7] at ~1.5μm, matching perfectly to the third telecommunications window, in a fibre which is compatible with telecom fibre, and which can be readily pumped by a diode laser to give high gain (in excess of 30dB, i.e. an intensity gain of 1000). These, and other attractive features of EDFAs have revolutionised the field of optical fibre communications.

While the EDFA has received the greatest share of attention, there is also a growing appreciation that fibre lasers and amplifiers have a great deal more to offer. For example, as a result of developments in fibres based on heavy metal fluoride

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glasses, there are now seen to be very exciting prospects for compact, visible, sources in the form of blue, green and red fibre lasers pumped by infrared diode lasers[8-13]. There is also a growing realisation that while fibre lasers may have very low threshold pump powers, this does not imply that they are necessarily low power devices and indeed it has been demonstrated that powers in excess of 1 watt are achievable from diode-pumped fibre lasers[14]. The broadened lines of rare-earth ions in glasses means that significant tuning ranges are available, in some cases[15] broader than the range typically offered by a dye laser, and yet despite this broad linewidth it has been possible to demonstrate very narrow linewidth operation (a few kHz) in single-frequency fibre lasers[16]. By contrast, on the other hand, the high gain can allow "mirrorless lasing", resulting in a broad, mode-less continuum as a result of amplified spontaneous emission (ASE)[17]. The broad gain profile has also been exploited in numerous demonstrations of self-mode-locked operation of fibre lasers where soliton pulse propagation behaviour is clearly implicated[18,19].

Thus the range of operating conditions, for fibre lasers, in power, wavelength, spectral and temporal behaviour, provides a very rich field for investigation and exploitation. In this brief review we therefore concentrate on basic features of fibre lasers and discuss particular lasers mainly as a means of illustrating general ideas. A list of laser transitions that have so far operated as fibre lasers is also provided with appropriate references. In fact the number of publications on fibre lasers is growing very rapidly and the list provided in this review is only a very small fraction of the total. Many further references, and an extensive review of fibre lasers and amplifiers can be found in the book edited by France[20].

BACKGROUND

The most striking feature of fibre lasers and amplifiers is the very high gain that can be achieved for very modest pump power, when the active core has the typical dimensions of a monomode fibre (few microns diameter) and the fibre is pumped by end-launching of the pump into the core. A figure of ~ 10dB gain per milliwatt of absorbed pump power has been reported for the EDFA[21]. Another striking feature is the very low pump power needed to saturate the pump transition, typically a few milliwatts. Even with this very low power, most of the population can be excited out of the ground level so that a three-level laser takes on the character of a four-level laser, i.e. having an essentially empty lower laser level, when a few milliwatss of pump are used. The ease with which a strong inversion can be produced has enabled laser operation to be achieved on many transitions which had not previously been operated in bulk form, including transitions with very low quantum efficiency. We begin therefore by giving a simple analysis which leads to an expression for the gain per unit of absorbed power.

We assume the fibre to have a step-index-profile, with refractive indices n_{co}, n_{cl} in the core and cladding respectively and a core diameter of 2a. It is customary to define a quantity, referred to as the V-value, which, for light of wavelength, λ, (in vacuum), is given by[22]

$$V = \frac{2\pi a}{\lambda} (n^2_{co} - n^2_{cl})^{1/2} \tag{1}$$

The quantity $(n^2_{co} - n^2_{cl})^{1/2}$ is known as the Numerical Aperture (NA) and defines the maximum acceptance angle θ_m for the end-launched light incident on the core via

$$\sin\theta_m = \text{NA} \qquad (2)$$

For the fibre to be monomode at the wavelength λ (ie for the LP_{11} mode to be cut off, leaving only the LP_{01} able to propagate), V must be less than 2.4. With typical values inserted in Equation (1), such as $\lambda = 1\mu m$ and $NA = 0.15$, then for $V = 2.4$, one has a $\sim 2.5\mu m$. Since the small core area leads to the high gain it is beneficial to minimise a. This can be done by using as large an NA as possible, although this will generally be limited by the maximum available index difference. One can also operate with a V-value somewhat smaller than 2.4, hence a smaller value of a, but for much smaller V-values the problems of bending loss can become significant[23].

We now consider a 4-level laser, with energy levels 1-4 as shown in Figure 1, and population densities N_1, N_2 etc respectively. The upper laser level, 3, has a lifetime τ, the lower laser level, 4, is assumed empty, and the emission cross-section for the laser transition 3-4 is σ_l. Pumping is from level 1 to level 2, with subsequent decay to level 3 and we shall assume a pumping quantum efficiency ϕ_p, this being the fraction of absorbed pump photons that yield an ion in level 3.

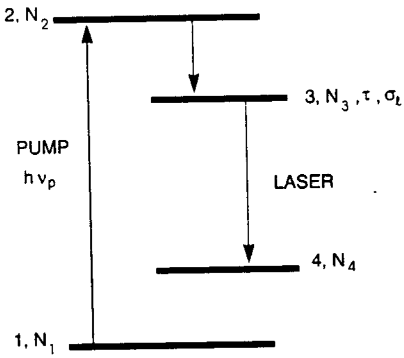

Figure 1. Schematic 4-level laser. For a true 3-level laser, the lower laser level, 4, and the ground level, 1, are the same.

Suppose that a continuous pump power P is absorbed in the fibre core and that the laser is below threshold, so that stimulated emission does not contribute to de-excitation from level 3. Then the total rate of excitation of population into level 3 is $P\phi_p/h\nu_p$ and this must equal the rate of de-excitation, ie

$$P\phi_p/h\nu_p = \frac{\int_0^l N_3(z)\,dz.\ A_{core}}{\tau} \qquad (3)$$

where A_{core} is the core area, and l is the fibre length

The gain (ie gain exponent) at frequency ν is given by $\sigma_l(\nu)\int_0^l N_3(z)\,dz$, ie

$$\text{gain} = \frac{\sigma_l(\nu)\tau\, P\phi_p}{h\nu_p\, A_{core}} \qquad (4)$$

This can be re-expressed, by making the following substitutions:

$$\tau = \phi_r \, \tau_r \tag{5}$$

where τ_r is the radiative lifetime corresponding to the laser transition, ϕ_r is the radiative quantum efficiency, (ie the fraction of ions in the upper level that decay via radiation on the laser transition) and[24]

$$\tau_r = \frac{\lambda_l^2}{8\pi n^2 \int \sigma_l(\nu) d\nu} \tag{6}$$

so that the gain, expressed in dB/W becomes

$$\text{gain(dB/W)} = \frac{4.3\ \sigma_l(\nu)}{\int \sigma_l(\nu) d\nu} \quad \frac{\phi (\text{NA})^2}{2 n^2 V^2 h\nu_p} \tag{7}$$

where $\phi = \phi_r \phi_p$

Taking the case of a Lorenztian line, for which[24]

$$\sigma_l(\nu) \ / \int \sigma_l(\nu) d\nu = 2/\ \pi\ \Delta\nu \ (\text{FWHM}) \tag{8}$$

and assuming $V = 2.4$ yields

$$\text{gain (dB/mW)} = (\text{NA})^2\ \phi\ /(10^4 \Delta\nu h\nu_p) \tag{9}$$

For a three level laser one can derive an appropriate analytical expression very similar to (9), ie

$$\text{gain (dB/mW)} \sim \frac{(I_p/I_{sat} - 1)}{(I_p/I_{sat} + 1)} \ (\text{NA})^2\ \phi\ /(10^4 \Delta\nu h\nu_p) \tag{10}$$

where I_{sat} is the saturation intensity for the pump transition, i.e. $I_{sat} = h\nu_p/\sigma_A\tau$ where σ_A is the absorption cross-section.

From Equation (10) it is seen that for $I_p >> I_{sat}$ the gain expression for the three level laser is essentially the same as for the four-level laser, as expected on the basis that most of the ground state population is excited so that the lower laser level is essentially empty.

In practice many laser transitions in fibres involve a final laser level which is an excited Stark level of the ground manifold, which is not completely empty, so that one deals in practice with a system that is intermediate between 3- and 4-level ("quasi-3-level" or "quasi-4-level").

It is instructive to look at the typical magnitude of gains indicated by Equations (9) and (10). In the case of Nd-doped fibre, pumped at ~0.8μm, taking the pumping quantum efficiency to be ~1 and for lasing at ~1μm the radiative quantum efficiency into the 1μm transition to be ~0.5 (emission also occurs at 1.3μm and ~0.94μm [25-27]). The linewidth is typically 3THz. With an NA of 0.15 this implies a gain of 1.5dB/mW.

A somewhat larger figure has been achieved in Er-doped silica, where $\phi \sim 1$, the pump wavelength can be longer (eg 0.98μm), and where a large NA has been deliberately used to enhance the gain, giving up to 11dB/mW [21].

These very high gains have a number of important consequences. First it means that diode lasers can be used as pumps and readily produce gains of 20dB or more. Thus one has available a very practical means of pumping. It also means that in many situations high losses can be tolerated. This can give greater freedom of design in a fibre laser resonator where the inclusion of a large number of lossy elements need not preclude efficient low threshold operation. With such high gains it is easy to achieve oscillation from the bare, uncoated fibre ends. This oscillation can be suppressed by such means as immersing the fibre ends in index-matching liquid, use of antireflection coatings, or of deliberately angled ends. Even with complete suppression of feedback, at sufficiently high gains, typically 30-40dB per single pass, the process of amplified spontaneous emission (ASE)[17] will take place with high efficiency and limit the achievable gain. This corresponds to a situation where photons spontaneously emitted at one end of the fibre are amplified on a single pass to an intensity that significantly depletes the gain. Such conditions can be readily achieved with diode-laser pumping.

The ability to produce high gain for modest pump power opens up the possibility of achieving laser oscillation on transitions of low quantum efficiency[17]. Even quantum efficiencies as low as 10^{-3} can be successfully exploited since this would still imply gains of several dB/watt. With care over the cavity design, losses can be kept down to a fraction of a dB so that thresholds of $\sim$100mW are not unreasonable for these low quantum efficiency transitions. It should also be noted that a low quantum efficiency need not imply a low slope efficiency for the laser. While the threshold varies as ϕ^{-1} (see Equation (9)), the slope efficiency varies as ϕ_p and does not depend on the radiative quantum efficiency ϕ_r. So, if the low quantum efficiency ϕ arises from a low ϕ_r, but $\phi_p \sim 1$, then although the threshold is increased by the low ϕ_r, the slope efficiency can still approach unity since, once threshold is exceeded, each absorbed pump photon can yield a laser photon. In fact the slope efficiency $\sim \phi_p(\nu_l/\nu_p)T/(L+T)$ where T is the output mirror transmission and L represents all other losses per round trip.

Another benefit of the high gain is that it can allow oscillation to be tuned into the far wings of the laser transition since enough gain can still be accessed in these regions. Generally the tuning extent is in fact limited, not by any inherent insufficiency of gain in the wings, but by excessive gain at line centre where ASE will set in and limit the gain. Substantial tuning ranges have been achieved in Yb [5,28] and Tm [29,30], 1.01-1.17μm and 1.65-2.05μm, respectively, before ASE limitations set in. By careful resonator design, to minimise the losses at the desired wavelength in the wings, it should be possible to achieve even wider tuning ranges on these and other transitions. With three-level lasers the effects of ASE at line centre can be countered by using a longer length of fibre so that at the distant end (from the pump) the pump intensity has dropped to a level which does not give sufficient inversion for net gain at line centre. In the long wavelength wing where the emission approaches a four level character, involving termal Stark levels which are above the ground level, gain is achieved for a smaller population in the upper laser level. Thus line centre ASE can be suppressed while gain is accessible in the long wavelength wing.

The last part of the above discussion indicates that in practice, for many of the broadband transitions of rare-earth dopants, in glass, it is not appropriate to refer to the laser level scheme as simply a "3-level laser" or a "4-level laser" since in practice the character of the emission can vary from essentially pure 3-level to pure 4-level, (ie empty laser level) as the emission wavelength goes from line centre to the long wavelength limit. In practice, for the purpose of calculating gain, all that is needed are the absorption and emission cross-sections $\sigma_a(\nu_l)$, $\sigma_e(\nu_l)$, and the population densities N_3

and N_1 ($=N_4$, where we have assumed level 4 and level 1 are the same manifold, see Figure 1). The gain exponent is then

$$\int_o^l (N_3(z)\sigma_e(\nu_l) - N_1(z)\sigma_a(\nu_l))dz$$

The emission cross-section can be calculated from the observed fluorescence emission, combined with the known radiative decay rates[31]. $N_3(z)$ and $N_1(z)$ are calculated from the following equations (11)-(13):

$$dI_p(z)/dz = -\alpha_p(I_p,z)I_p(z) \tag{11}$$

where $\alpha_p(I_p,z)$ is the pump absorption coefficient at location z. α_p is given by

$$\alpha_p(I_p,z) = \frac{\alpha_p(o,z)}{1 + I_p(z)/I_s} \tag{12}$$

where the pump saturation intensity I_s is given by

$$I_s = h\nu_p/(\sigma_e(\nu_p) + \sigma_a(\nu_p))\tau \tag{13}$$

With (13) and (12) substituted into (11) one can solve for $I_p(z)$, thus from (13) obtain α_p as a function of z, and then by using the relation

$$\begin{aligned} \alpha_p(z) &= N_1(z)\sigma_a(\nu_p) - N_3(z)\sigma_e(\nu_p) \\ &= N_1(z)\sigma_a(\nu_p) - (N_0-N_1(z))\sigma_e(\nu_p) \end{aligned} \tag{14}$$

$N_1(z)$ can be calculated, hence $N_3(z) = N_0-N_1(z)$ is found and finally the gain exponent can be calculated from

$$\int_o^l (N_3(z)\sigma_e(\nu_l) - N_1(z)\sigma_a(\nu_l))dz$$

Here we have described a general procedure for calculating gain from a given length of fibre, where the pump wavelength may in general overlap with the laser emission transition, so that pump photons cause both excitation and de-excitation. This degree of generality is necessary in circumstances where so-called "in-band" pumping is used, as for example in the EDFA where a pump at ~1.48μm can be used[32] to produce gain at ~1.53μm so that the pump is essentially in the short wavelength wing of the pump band but also has a significant overlap with the short wavelenth wing of the emission band. Another important example of such in-band pumping is the 0.8μm transition in Tm, where pumping at ~0.78μm produces gain at ~0.81μm [33]. Where the pump band is well separated from the emission band the analysis is of course simpler and one notes for example that the saturation intensity given in Equation (13) then reduces to the familiar form $I_s = h\nu_p/\sigma_a(\nu_p)\tau$, as quoted after Equation (10).

The saturation power, P_s, is simply I_sA_{core}, and it is interesting to note how low a value the saturation power can have typically. In erbium-doped silica with

$\sigma_a \sim 4\text{x}10^{-25}\text{m}^2$ for 980nm, and $\tau \sim 10^{-2}$s, one has $I_s \sim 5\text{x}10^7\text{w/m}^2$, and for a 6$\mu$m diameter, P_s is ~1.5mW. Thus, strong saturation by the pump is a typical situation in practice. This fact emphasises the potential of fibre lasers for sequential pumping to higher levels since with powers of a few milliwatts it is possible to essentially empty the ground level and put all the population in an excited level from which further excitation is possible.

Since the pump can strongly saturate the absorption the pump will propagate much further into the fibre than suggested simply by the extinction length calculated from the small-signal pump absorption coefficient. In fact, a useful approximate result is that if the pump power at the input is x times the saturation power, it will only drop to the saturation power after travelling a distance of ~x times the small signal extinction length. So, for a three level laser, pumped by x times the saturation power, the gain would increase with fibre length, up to x extinction lengths, and thereafter decrease as the medium would no longer be inverted at greater distances along the fibre. One sees that 3-level lasers therefore have an optimum length in terms of maximum gain and that this length is pump-power dependent, increasing with increasing pump power. For four-level lasers, on the other hand, assuming no loss, there would be no optimum length, gain being greatest for infinite length. In practice, of course, finite losses imply an optimum length even for four-level systems. Since the character of the emission can vary from 3- to 4-level across an emission band, so the optimum length for maximum gain is a function, not only of pump intensity but also of emission wavelength.

As a final word on this background material it should be added that the procedure for calculating gain as described here is an approximate one, susceptible to straightforward numerical calculation. In practice, for a detailed and realistic modelling of actual gain it may also be necessary to include a number of other features, such as the fact that the dopant may not be uniformly distributed across the core. Also the fact that the pump and signal modes are not top-hat functions needs to be included in the form of overlap integrals[34], and the model also needs to include the fact that the saturation behaviour now has a transverse dependence. Finally at high gains the effect of ASE[35] must also be included since it affects the gain, by saturation, and also influences the noise behaviour of the amplifier.

A Survey of Fibre Laser Transitions

Figure 2 shows the energy levels of the tri-valent rare-earth ions and at a first glance suggests a very wide choice of potential laser transitions.

In practice many of the levels have very short lifetimes, so they are not good candidates for laser levels. The main mechanism responsible for shortening level lifetimes is decay to a lower level via multiphonon emission, where conservation of energy requires that the total energy of the created phonons equals the energy difference, ΔE, between the initial and final levels of the ion. This nonradiative process has a decay rate W_{nr} that obeys a relation[36],

$$W_{nr} = B\exp[-\alpha(\Delta E - 2h\nu)] \tag{15}$$

where $h\nu$ is the highest phonon energy in the phonon spectrum of the host. The equation shows that the decay rate in a given host (fixed α, B, $h\nu$) decreases orientially with increasing energy gap ΔE and the multi-phonon decay rate is lower in materials for which the maximum phonon energy is lower. This feature has given considerable

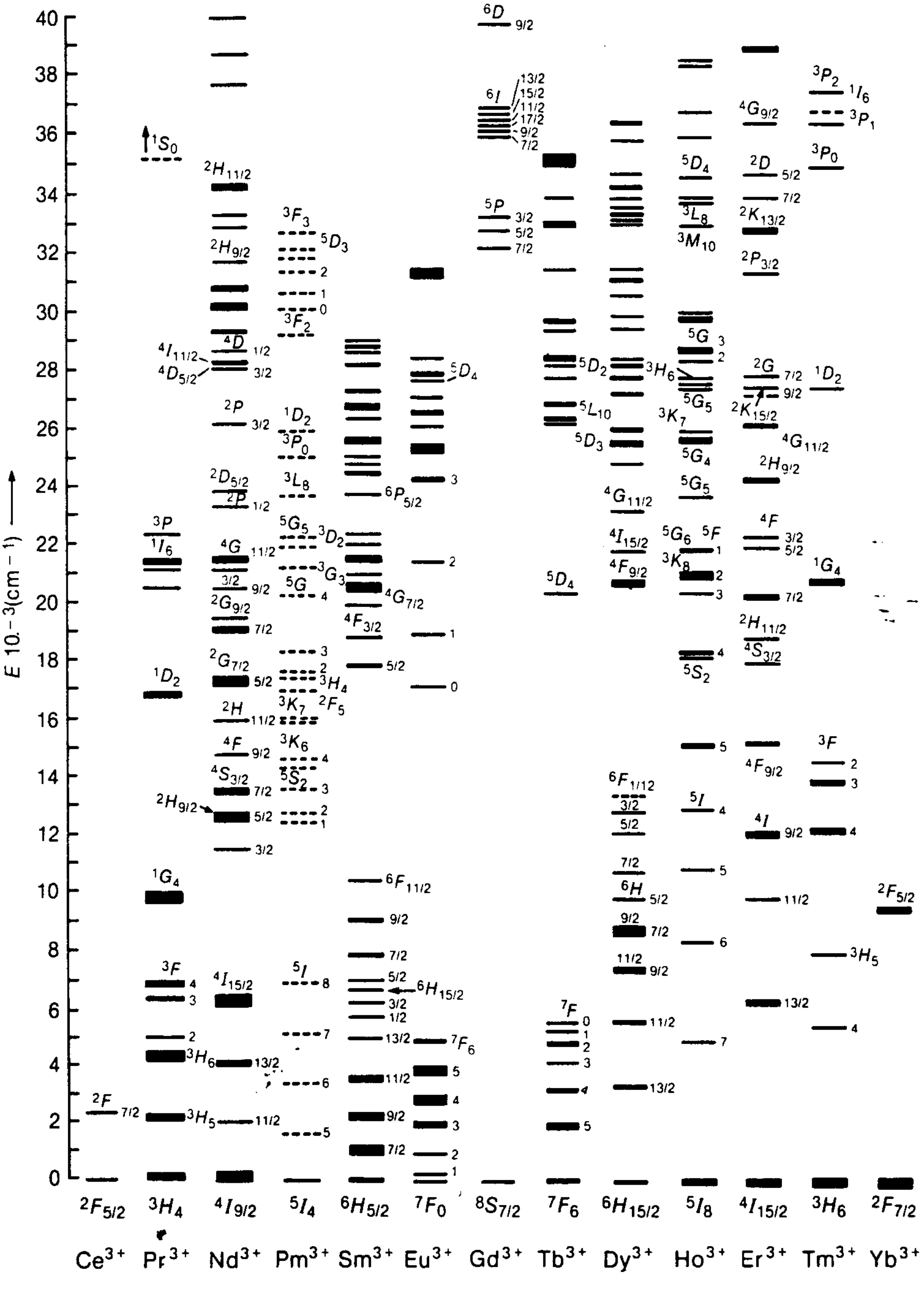

Figure 2. Energy levels of tri-valent rare-earth ions (after ref 70).

prominence in recent years to glasses with lower phonon energies, such as the heavy-metal fluoride glasses[37,38], of which the Zirconium Fluoride glass known as ZBLAN[37] has been most extensively used. Particular interest in the rare-earth doped ZBLAN fibres has arisen for two reasons. The first relates to the search for a fibre amplifier suitable for the important telecom window at ~1.3μm, and the second relates to their potential for visible upconversion lasers. A third reason, which is gaining prominence, is the capability for longer wavelength infrared laser operation (to ~3.5μm so far[39]). The lower phonon energy is then necessary for two reasons first to prevent multiphonon decay across the small energy gap of the infrared transition, and secondly to provide good transparency in the infrared by virtue of the infrared absorption edge being shifted to longer wavelengths in low-phonon-energy materials.

The search for a suitable fibre amplifier for the 1.3μm window has proved much less straightforward than for the 1.5μm window. A transition at 1.3μm in Nd^{3+} ($^4F_{3/2}$ - $^4I_{13/2}$) was found to suffer from strong excited state absorption (ESA) at the 1.3μm signal wavelength[26], this absorption being particularly strong in a silica host. While the ESA was found to be weaker in Nd:ZBLAN[40], it was still troublesome and in any case the rather weak 1.3μm transition suffered from the problem of there being a much higher gain (with the associated problem of ASE) on the 1μm transition which shares the same initial level. The search for a alternative 1.3μm transition has now centred on the $^1G_4$ - $^3H_5$ transition in Pr^{3+}. However the $^1G_4$ level has other levels below it, much closer than $^3H_5$, (the $^3F_4$ level is only ~3000cm^{-1} below $^1G_4$), so that multiphonon decay out of $^1G_4$ precludes the use of silica host. The decay rate of Pr^{3+} $^1G_4$ in ZBLAN is much reduced (although still significantly shortened by multiphonon decay) and appears to offer a viable 1.3μm amplifier. In fact, a very rough guide to the effect of multiphonon decay would indicate that an energy gap of ~4500cm^{-1} in silica, and ~3000cm^{-1} in ZBLAN are the minimum required to avoid rapid multiphonon decay.

The role of multiphonon decay is also of very great importance to upconversion lasers, where the aim is to pump an ion to a high energy level by sequential absorption of two or more photons, followed by laser emission of a single more energetic photon. For this to succeed the intermediate level(s) and the upper laser level must not suffer from an excessive rate of multiphonon decay. This again puts hosts with low phonon energies at an advantage and it is notable that all of the upconversion fibre lasers to date (in Tm[13,41], Ho[8], Er[11,12], Pr[9,10]) have all made use of a ZBLAN host. The use of ZBLAN has greatly extended the range and number of laser transitions and there are undoubtedly very many more laser transitions yet to be demonstrated in ZBLAN fibre. The success of ZBLAN has also prompted the search for alternative low phonon energy glasses which may lend themselves to simple preparation and simpler fibre fabrication than is the case for ZBLAN. The table below gives a list of fibre laser transitions observed to date, with representative, but not exhaustive, references, where detailed performance data can be found. Where a range of wavelengths is indicated this corresponds to the tuning range that has been achieved.

From the wealth of material represented in the table we shall single out Tm fibre lasers for further discussion since Tm offers a good example for illustrating a number of general points and for showing the rich variety of laser characteristics available in a fibre geometry. The relevant energy levels of Tm^{3+} are shown in Figure 3.

The first demonstration of laser action in Tm^{3+}-doped fibre was in silica fibre[61], on the $^3H_4$ - $^3H_6$ transition at ~1.9μm, by pumping at ~0.8μm into the $^3F_4$ level. Rapid multiphonon decay from this level leads to efficient population of $^3H_4$. Low threshold, efficient operation has been achieved on this transition, including diode-pumped operation[30] and widely tunable operation[29,30]. The $^3H_4$ level lifetime is

Table 1. Fibre laser transitions

Wavelength (μm)	Element	Transition	Ref
3.4	Er	$^4F_{9/2}$ - $^4I_{9/2}$	39
2.9 (2.83-2.95)	Ho	$^5I_6$ - $^5I_7$	42
2.75 (2.70-2.83)	Er	$^4I_{11/2}$ - $^4I_{13/2}$	43
2.3 (2.25-2.5)	Tm	$^3F_4$ - $^3H_5$	44
2.04	Ho	$^5I_7$ - $^5I_8$	45,46
1.9 (1.65-2.05)	Tm	$^3H_4$ - $^3H_6$	29,30,47
1.72	Er	$^4S_{3/2}$ - $^4I_{9/2}$	48
1.66	Er	$^2H_{11/2}$ - $^4I_{9/2}$	48
1.55 (1.52-1.62)	Er	$^4I_{13/2}$ - $^4I_{15/2}$	20
1.47	Tm	$^3F_4$ - $^3H_4$	47,49
1.38	Ho	$^5S_2$, $^5F_4$ - $^5I_5$	45
1.34	Nd	$^4F_{3/2}$ - $^4I_{13/2}$	40,27
1.31	Pr	$^1G_4$ - $^3H_5$	50-52
1.2	Ho	$^5I_6$ - $^5I_8$	53
1.08	Pr	$^1D_2$ - $^3F_{3/4}$	54
1.06 (1.05-1.14)	Nd	$^4F_{3/2}$ - $^4I_{11/2}$	20
1.04 (1.01-1.17)	Yb	$^2F_{5/2}$ - $^2F_{7/2}$	15,28
0.98	Er	$^4I_{11/2}$ - $^4I_{15/2}$	55
0.975	Yb	$^2F_{5/2}$ - $^2F_{7/2}$	15
0.94 (0.9-0.95)	Nd	$^4F_{3/2}$ - $^4I_{9/2}$	26,56
0.91	Pr	$^3P_0$ - $^1G_4$	57
0.88	Pr	$^3P_1$ - $^1G_4$	57

Table 1. (cont'd)

Wavelength (μm)	Element	Transition	Ref
0.88	Pr	${}^1D_2$ - ${}^3H_6$,${}^3F_2$	54
0.85	Er	${}^4S_{3/2}$ - ${}^4I_{13/2}$	58
0.8	Tm	${}^3F_4$ - ${}^3H_6$	33
0.715	Pr	${}^3P_0$ - ${}^3F_4$	57,9,60
0.695	Pr	${}^3P_1$ - ${}^3F_4$	57,9,60
0.651	Sm	${}^4G_{5/2}$ - ${}^6H_{9/2}$	59
0.635	Pr	${}^3P_0$ - ${}^3F_2$	57,9,10,60
0.61	Pr	${}^3P_0$ - ${}^3H_6$	57,9,60
0.55	Ho	${}^5S_2$ - ${}^5I_8$	8
0.546	Er	${}^4S_{3/2}$ - ${}^4I_{15/2}$	11,12
0.520	Pr	${}^3P_0$ - ${}^3H_5$	9,60
0.491	Pr	${}^3P_0$ - ${}^3H_4$	9
0.48	Tm	${}^1G_4$ - ${}^3H_6$	41
0.455	Tm	${}^1D_2$ - ${}^3H_4$	41

nevertheless somewhat shortened by nonradiative multiphonon decay, from an expected radiative lifetime of ~6 sec to a few hundred microseconds. This raises the threshold, but as indicated earlier does not affect the slope efficiency and in practice slope efficiencies well in excess of the radiative quantum efficiency of ${}^3H_4$ have been observed. In fact the possibility exists for pumping quantum efficiencies in excess of 100% and approaching 200% by energy transfer between Tm ions, where a Tm ion in ${}^3F_4$ shares its energy with a neighbouring unexcited Tm ion (in ${}^3H_6$), so that both end up in ${}^3H_4$. For this to occur efficiently however the Tm - Tm transfer rate must exceed the multiphonon decay rate ${}^3F_4$ - ${}^3H_5$. This situation would be favoured in a host of low phonon energy such as ZBLAN, and also requires a high dopant concentration.

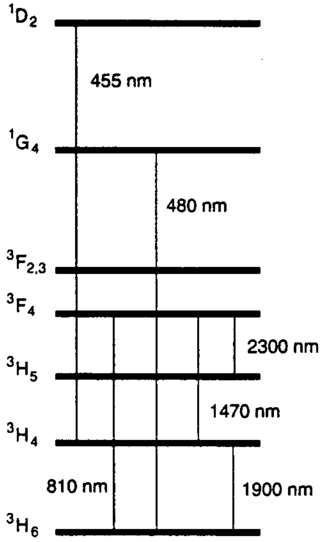

Figure 3. Energy levels of Tm^{3+} with demonstrated fibre laser transitions and their wavelengths indicated by vertical lines.

Tm doped ZBLAN shows many more laser transitions than in silica as a result of the reduced decay rate of the excited levels[47,62]. From $^3F_4$, laser transitions at 2300nm ($^3F_4$-$^3H_5$), 1470nm ($^3F_4$--$^3H_4$) and 810nm ($^3F_4$-$^3H_6$) are all observed. In fact in ZBLAN the $^3F_4$-$^3H_6$ branching ratio ($\sim$0.88) is dominant, so that when pumping the $^3F_4$ level the pumping quantum efficiency for the $^3H_4$ level is now much reduced compared to the case in silica. Possible ways of increasing the pumping efficiency of $^3H_4$ include the use of high doping levels to allow Tm - Tm energy transfer as described above, or enforcement of lasing on the 2300nm and/or 1470nm transitions[47,63]. The lifetime of $^3H_4$ is essentially equal to the radiative lifetime of ($\sim$ 6 msec) as multiphonon decay from $^3H_4$ level is suppressed in ZBLAN. In fact, for optimum operation of the $^3H_4$-$^3H_6$ laser (minimum threshold) one ideally requires a host glass with maximum phonon energy intermediate between those of ZBLAN and silica. In this way nonradiative decay can efficiently channel population from $^3F_4$ to $^3H_4$, while the $^3H_4$ lifetime remains at essentially the pure radiative value. This outcome has indeed been achieved in Tm-doped lead germanate glass fibre[64], this glass composition having been deliberately chosen for its intermediate phonon energy. As expected this has shown a lower threshold for 1900nm lasing than either the ZBLAN or silica fibre.

Another way of pumping the $^3H_4$ level and avoiding problems of inefficient branching out of the $^3F_4$ level is to pump into the $^3H_5$ level. However peak absorption is at an inconvenient pump wavelength of $\sim$ 1.2μm for which sources are not readily available. Nevertheless the absorption in the high energy wing of the $^3H_6$ - $^3H_5$ is sufficient in Tm silica to allow pumping with a NdYAG laser at 1.064μm[65]. In this way high power operation of a Tm fibre laser has been achieved (> 1W) at 1.9μm[66] by virtue of the fact that a copious amount of pump power was available with a good beam quality that allowed efficient launching into the core.

While pumping with the 1.064μm source, a considerable amount of blue side-light emission could be seen, corresponding to upconversion pumping, via three absorbed photons; $^3H_6$ - $^3H_5$, followed by relaxation to $^3H_4$, then $^3H_4$ - $^3F_{2,3}$, followed by relaxation to $^3F_4$, and finally $^3F_4$ to $^1G_4$ from which emission at 480nm, $^1G_4$ - $^3H_6$ was observed. A detailed study[67] of this upconversion pumping led to the conclusion that it would be greatly enhanced in ZBLAN fibre, which therefore presented the preferred route to upconversion lasing. The first fibre upconversion laser was in fact demonstrated[41] in Tm:ZBLAN, but using two red pump photons rather than infrared. Very recently however Tm:ZBLAN has been shown[13] to have excellent upconversion laser performance when infrared pumped via the three photon route described above, but using longer wavelength pump radiation ($\sim 1.12\mu m$) to enhance the absorption cross section on the pumping stages.

This completes a brief survey of the variety of lasing processes that can be observed in Tm doped fibres. It is clear that there is a need for such more detailed characterisation and that there is great scope for further optimisation of all of the laser transitions reported. Particular interest is attached to the blue upconversion laser, since with its already demonstrated efficiency of $\sim 30\%$ (from pump photons to output), it appears to be a particular attractive candidate for the much sought after compact blue light source.

Concluding Remarks

In this review we have given emphasis to the wide spectral coverage that is now possible via fibre lasers. Here the prospect is that ultimately most of the spectral range from $\sim 0.4\mu m$ to $\sim 4\mu m$ should be continously covered with diode-pumped fibre lasers. Applications of such lasers may make various demands on the lasers' performance, such as single-frequency operation, mode-locked operation, Q-switched operation, tunable operation, high power operation etc etc. All of these modes of operation have been demonstrated in fibre lasers, and while the demonstrations have perhaps been confined so far to particular laser transitions, the techniques involved are generally capable of being applied very widely, so that these laser performance characteristics should ultimately be available across the whole spectral range indicated above.

Meanwhile rapid progress is being made on the development of fibre components, such as fibre Fabry-Perot etalons, highly reflective Bragg gratings, written directly into the fibre core, fibre couplers, isolators etc, so that we can look forward to fibre lasers with a high degree of temporal and spectral control with the entire laser in the form of a rugged, compact, all-fibre geometry.

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