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PHYSICS OF FIBRE LASERS

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Abstract

Monomode fibres doped with rare-earth ions provide many attractive features as laser devices, including pumping by diode-lasers, wide tuning capability, Q-switched and mode-locked operation, and offer an effective route to new laser transitions. This paper highlights some of these features and provides illustrations taken from recent experimental results.

The glass fibre laser, invented by Elias Snitzer[1] in 1961, has been the subject of considerable recent interest since the demonstration by Mears et al[2] in 1985 of monomode fibre laser devices based on silica fibres. Monomode fibres doped with rare-earth impurities offer a number of features which make them attractive as lasers or amplifiers and the aim of this paper is to highlight some of these features and provide illustrations taken from recent experimental results. We also provide an extensive bibliography relating to fibre lasers.

Some of the features of interest are listed below:

* Simplicity of fabrication
* Excellent optical quality
* Freedom from thermal distortion
* Low threshold, allowing pumping by diode lasers, cw operation of 3-level lasers, and offering possibilities for new laser transitions
* High gain
* High efficiency
* Wide bandwidth, thus allowing significant tuning ranges, and short pulse operation via mode-locking
* Compatibility with monomode fibre devices such as couplers, modulators, integral grating devices etc.
* Low loss, thus allowing the use of long-fibre lengths, with consequences such as large nonlinear effects, large dispersion, ability to pump via weak absorption, etc.

For silica-based fibres, various fabrication techniques have been described (see Urqhart[3] for a recent review). These include a variation on the MCVD process in which the dopant is introduced as a vapour[4,5], and a more versatile solution-doping technique[6,7] which allows the dopant to be introduced from solution. The latter technique has allowed co-doping with different ions, at concentration levels sufficient to

achieve an efficient energy-transfer laser, as for example in the Yb:Er system[8]. For fibres based on fluorozirconate glass, quite different fabrication techniques are required, involving casting in a mould to make the preform[9], and techniques for fabricating monomode fibres are still at an early stage of development. Fluorozirconate glass fibres offer features which extend the capabilities of silica fibres, such as good IR transmission to longer wavelengths[9] and reduced rates of nonradiative decay as a result of the lower phonon energies. A consequence of the slower non-radiative decay is that laser emission has been observed in fluoride glass fibres from levels which in silica decay too fast to permit lasing. The table below lists those transitions reported to have lased to date (Dec. '88) in both silica and fluoride glass fibres.

Ion	Transition	Host	Wavelength (μm)	References
Nd^{3+}	$^4F_{3/2} - {}^4F_{11/2}$	SiO_2	1.055 - 1.14	1,2,7,10-26
	$^4F_{3/2} - {}^4I_{9/2}$	SiO_2	0.9 - 0.95	27-29
	$^4F_{3/2} - {}^4I_{13/2}$	SiO_2	1.39	30
Er^{3+}	$^4I_{13/2} - {}^4I_{15/2}$	SiO_2	1.53 - 1.60	33-41,8
Pr^{3+}	$^1D_2 - {}^3F_4$	SiO_2	1.084	42,43
	$^1D_2 - {}^3F_2$	SiO_2	0.886	43
Sm^{3+}	$^4G_{5/2} - {}^6H_{9/2}$	SiO_2	0.651	44
Yb^{3+}	$^2F_{5/2} - {}^2F_{7/2}$	SiO_2	1.01 - 1.162 0.974	45,48,49
Tm^{3+}	$^3H_4 - {}^3H_6$	SiO_2	1.88 - 1.96	50
Nd^{3+}	$^4F_{3/2} - {}^4I_{11/2}$	Fluoride	1.05	55
	$^4F_{3/2} - {}^4I_{13/2}$	Fluoride	1.35	31,32
Er^{3+}	$^4I_{13/2} - {}^4I_{15/2}$	Fluoride	1.56	
	$^4I_{11/2} - {}^4I_{13/2}$	Fluoride	2.7	53
Ho^{3+}	$^5I_7 - {}^5I_8$	Fluoride	2.08	54
	$^5S_2, {}^5F_4 - {}^5I_5$	Fluoride	1.38	54
Tm^{3+}	$^3F_4 - {}^3H_5$	Fluoride	2.3	52

Below we list some comments on the more noteworthy features of these transitions.

The Nd^{3+} $^4F_{3/2} - {}^4I_{11/2}$ transition at around 1.06 μm is one of the most extensively studied transitions, having been implicated in each of the key developments of fibre lasers[1,7,10,2]. Operation on this transition has been demonstrated over a wide range of conditions. These include diode-pumped operation[11-14], Q-switched operation[15,11,16], mode-locked operation[17-19,14], tuned operation[20,21] and superfluorescent operation[22]. Operation with various resonator configurations has been demonstrated, including resonators with butted mirrors, with mirrors directly coated on the fibre ends[23], single

longitudinal mode operation in a fibre incorporating an integral grating[24,25], single longitudinal mode operation in a Fox-Smith resonator incorporating fibre loops as reflectors[25]. A summary of the performance characteristics reported to date include: thresholds of well below 1 mW, efficiencies of ~ 50%, single frequency operation with linewidth of ~ 1 MHz[25], mode-locked operation with bandwidth limited pulses of 20 psec[19], cw output power of 10 mw when diode-pumped[14], peak output power of ~ 100 w from a Q-switched diode-pumped laser[16], peak powers of ~ 1 kw in a mode-locked, Q-switched, diode-pumped laser[14], tuning over a range of 70-80 nm[20,21]. These results indicate some of the potential of fibre lasers.

For the Nd^{3+} $^4F_{3/2}$ - $^4I_{9/2}$ transition at ~ 0.9 μm, the lower laser levels lie in the ground manifold and therefore result in a 3-level character, due to the significant population in the lower laser level. Following the first observation of lasing on this transition in a fibre laser[27], tuned operation has been demonstrated[20,21], Q-switched and mode-locked operation[28], and diode pumped operation[29]. Generally performance levels are somewhat below those achievable on the $^4F_{3/2}$ - $^4I_{11/2}$ transition as a result of the 3-level character.

The Nd^{3+}, $^4F_{3/2}$ - $^4I_{13/2}$ transition, in the 1.3 μm region, suffers from excited state absorption[21] (ESA), a cause for some disappointment in view of the potential applications in optical communications for sources and amplifiers in this region. Lasing on this transition has been achieved in silica fibre[30], but the ESA forces operation at wavelengths too long (~ 1.4 μm) to be of interest for optical communications (this falls in a region of OH absorption). Fluoride glass fibres offer better prospects with reduced ESA problems, and shorter wavelength operation (1.33 -1.35 μm)[31,32].

The Er^{3+}, $^4I_{13/2}$ - $^4I_{15/2}$ transition at ~ 1.55 μm is of particular importance as it falls in the so called third transmission window of silica based communication fibres. Several different pump lasers have been used, the first operation being obtained with a 514 nm Argon laser pump[33]. An important breakthrough was made with the demonstration of pumping by a GaAlAs diode laser at 807 nm[34,35] since this offers the prospect of a very convenient package for in-line amplification in optical fibre communication systems operating at 1.55 μm. A problem that has been identified with pumping around 800 nm is that of ESA, of the pump radiation, which reduces the available gain[36]. Despite this the diode-pumped Er fibre amplifier may still prove to be a successful device, as the increased pump power requirements enforced by the ESA may be met using high brightness diode arrays which allow a significant fraction of their output to be coupled into a monomode fibre[37,14]. Meanwhile alternative approaches which reduce the ESA are being investigated. One of these[38] involves pumping with 980 nm radiation, for which ESA is absent, and has resulted in high gain, 24 dB for 11 mw of absorbed pump, i.e. 2.2 dB/mW. Another approach involves the use of fibre co-doped with Yb and Er, in which pumping takes place into the absorption band of Yb which then transfers its excitation to the Er[39]. The broad absorption band of Yb (~ 0.8 - 1.06 μm) allows pumping in regions away from the Er ESA. Results form this Yb:Er fibre include efificient pumping in the wavelength range of diode lasers (~ 0.8 μm)[40], NdYAG and NdYLF lasers[8,41] and demonstrate that the solution doping technique can achieve dopant concentrations sufficient to allow efficient energy transfer.

While the Nd^{3+} and Er^{3+} fibre lasers have so far received most attention there is a growing list of new fibre laser transitions, some of which have not previously been observed to lase in a glass host. An example of this is provided by the Pr^{3+} transitions $^1D_2$ - $^3F_4$ (~ 1.084 μm)[42] and $^1D_2$ - $^3F_2$ (~ 0.886 μm)[43], both of which have operated in a silica fibre, pumped by a cw Rhodamine 6G laser, but had not previously been reported in a glass host. Another example is provided by the Sm^{3+} doped fibre laser[44], operating on the $^4G_{5/2}$ - $^6H_{9/2}$ transition at 0.65 μm, this being the first report on lasing on this transition in any host and the first example of visible fibre laser.

Other transitions recently observed to lase in fibres include the Yb^{3+}, $^2F_{5/2}$ - $^2F_{7/2}$ transition[45], which in fact has two resolved transitions, a broad one centred at ~ 1.064 μm (4-level laser) and a narrower one at 0.974 μm (3-level laser). The 4-level transition has previously been observed to lase in bulk glass[46,47], but not the three-level transition. Some interesting features of the Yb^{3+} fibre laser are the very wide tuning range achieved (1.01 - 1.16 μm)[48], in part due to the absence of any limitation due to ESA, and the observation of efficient superfluorescent emission on the 3-level (0.974 μm) and 4-level (1.04 μm) transition[49].

Tm^{3+} provides another interesting example. When pumped at 797 nm it has produced lasing[50] on the $^3H_4$ to $^3H_6$ transition at ~ 1.85 μm. This (3-level) laser transition has previously been operated in pulsed fashion in bulk glass by Gandy et al[51]. The fluorescence emission in the fibre covers the range ~ 1.7 μm to 2.2 μm, thus offering this as a potential tuning range and with the additional attractive possibility of diode pumping. It is interesting to note that fluorozirconate fibre doped with Tm^{3+} has instead operated[52] at 2.3 μm on the $^3F_4$ - $^3H_5$ transition (we have used the level notation of Gandy et al[51] rather than of Esterowitz et al[52]), since the $^3F_4$ level does not undergo rapid non-radiative decay as in silica glass.

Further examples of the additional laser transition made possible by reduced non-radiative decay rates in fluorozirconate glass fibres are found in Er^{3+}, on the $^4I_{11/2}$ - $^4I_{13/2}$ transition at 2.7 μm[53], and Ho^{3+}, with transitions at [54] at 2.08 μm, $^5I_7$ - $^5I_8$ and at 1.38 μm, $^5S_2$, $^5F_4$ - $^5I_5$.

Summary

Developments in fibre lasers are taking place rapidly, with new laser transitions demonstrated and improved powers, efficiencies and gains. Fluuorozirconate fibres in particular offer the prospect of many more laser transitions with possibilities for energy transfer and up-conversion. Developments in diode lasers, enabling more pump power to be launched into monomode fibres[14] will play an important role in the future. New fibre geometries like the double-clad fibre[56] can also lead to efficient utilisation of pump power from high power diode arrays. With the increased power levels now being achieved in fibre lasers, particularly in Q-switched and/or mode-locked systems, nonlinear effects will become increasingly accessible and increasingly important.

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