Developments in solid state lasers

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Abstract

Three developments in solid state lasers are reviewed: tunable lasers; Nd-doped lasers pumped by diode lasers; optical fibre lasers.

Introduction

In this paper we review three areas of development in solid state lasers which have begun to attract considerable interest and effort in recent years and currently represent some of the most active areas of research. These are (1) tunable lasers, (2) Nd-doped lasers pumped by diode lasers and (3) optical fibre lasers. In one sense none of these areas is really new since the basic ideas were demonstrated experimentally around 20 years ago. So in 1963, Johnson et al[1] demonstrated tunable operation of a Ni:MgF_2 laser. In 1968 Ross[2] demonstrated pumping of a NdYAG laser by a GaAs diode laser, and in 1963, Young[3] demonstrated lasing in a fibre laser. Following these initial demonstrations each of these areas underwent a long period of quiescence and have now just reemerged as a result of other technological advances in the laser field. In the case of diode-laser pumped Nd lasers, the key technological advance has been the recent commercial availability of diode lasers with sufficient output power. In the case of fibre lasers the key advance has been the development of a technique for producing doped monomode fibres with very low loss[4]. In the case of tunable lasers, two advances stimulated renewed interest. On the one hand, a tunable laser material, alexandrite[5], was developed, which allowed direct flash lamp pumping and room temperature operation. This stimulated discoveries of other tunable laser materials based on Cr^{3+} as the dopant. On the other hand, the materials originally discovered by Johnson et al, Ni^{2+}:MgF_2 and Co^{2+}:MgF_2, and which required cryogenic temperatures for operation, were found to operate very efficiently and conveniently when pumped by a laser[6] rather than by flashlamp, as used by Johnson et al. This advance was dependent therefore on the availability of a NdYAG laser operating at $\sim$1.3 µm to act as the pump[6]. In fact a common theme in all three areas of development to be reviewed in this paper is the important influence that longitudinal pumping by a laser has exerted. A few preliminary remarks will therefore be made on this point.

Longitudinal-pumping by laser

Longitudinal pumping of the solid state laser medium by a beam from another laser confers a number of important advantages over transverse pumping, either by an incoherent or coherent pump. Longitudinal pumping allows a very small volume of the material to be pumped. If the length of material is L, then the pumped area can be $\sim L\lambda$ where λ is the pump wavelength. This follows from the fact that the pump beam can be focussed to a waist size w_0 such that the confocal parameter ($\equiv 2\pi w_0^2/\lambda$) equals the length L of the laser medium. This minimises the pumped volume. If L is chosen to be $\sim$ an extinction length for the pump, then the pump radiation will be efficiently absorbed. For efficient transverse pumping the transverse dimensions must also be $\sim$ an extinction length. So, longitudinal pumping allows a reduction in the pumped volume of typically three orders of magnitude (L/λ). This translates into a reduced threshold pump power by the same amount. An important result of this reduced pump input is a reduced heat load, with consequent reduction in the thermally-induced stress and birefringence in the pump material. Thus one of the major problems of solid state lasers, the need to remove heat by conduction, is greatly alleviated. In fact, an early illustration of the enhanced performance resulting from longitudinal pumping is given by the work of Kishida et al[7], who showed that cw pumping of a Nd phosphate glass laser by an argon laser could be accomplished without the thermal problems that have usually plagued attempts to obtain cw operation of glass lasers. Another advantage of longitudinal pumping is the convenience of dispensing with lamp supplies and cooling which otherwise clutter the pumping chamber. This advantage is particularly welcome when the laser medium is maintained at cryogenic temperatures.

A further step towards lower threshold and reduced heat load is achieved by going from a bulk medium to a guided medium such as an optical fibre waveguide[4,8]. For a monomode fibre the transverse dimensions of the doped core are of the order of the pump wavelength. The pumped area of the active region is therefore very small, typically two orders of magnitude less than in a bulk medium which is optimally pumped longitudinally. This again translates into a corresponding reduction of threshold. Thus one is presented with a glass laser medium for which the threshold pump power is of the order of a milliwatt or less[9], and where the pump intensity even for such a low power is sufficient to saturate the pump transition and allow cw laser oscillation even in a three-level system[10,11]. This illustrates in a very dramatic way the benefits to be gained from longitudinal laser pumping.

Tunable lasers

The $Co^{2+}:MgF_2$ and $Ni^{2+}:MgF_2$ lasers originally demonstrated by Johnson et al, still need low temperature operation despite the great improvements in performance conferred by laser pumping.

The typical resonator configuration used for these lasers is virtually identical to that used for colour centre lasers which also need liquid nitrogen cooling. Apart from this need for cooling the performance of these lasers shows an impressive range of capabilities, including the following; pulsed operation of $Co:MgF_2$ (pumped by a pulsed 1.3 μm $NdYAlO_3$ laser) producing 150 mJ, 1msec pulses at 50 Hz repetition rate, with an average power of ∿7w.[12]; Q-switched operation of $Co^{2+}:MgF_2$ to give a TEM_{00} mode output of ∿ 60 mJ in 150 nsec pulses[13]; tuning of $Co^{2+}:MgF_2$ over the range 1.5 - 2.3 μm[13,14]; mode locked operation of $Co^{2+}:MgF_2$ and $Ni^{2+}:MgF_2$ to give pulse durations of 20 - 30 psec[15]; narrow linewidth performance (<1.5 MHz) for a $Co^{2+}:KZnF_3$ laser[16].

Around the same time that Moulton was rekindling interest in Co^{2+} and $Ni^{2+}:MgF_2$, another tunable laser material appeared on the scene, bringing two attractive attributes: room temperature operation and efficient flash lamp pumped operation. This was alexandrite[5] (chromium doped chrysoberyl). While continuing to be an interesting laser material, alexandrite no longer holds a monopoly of interest, as its discovery stimulated a search for other chromium doped tunable lasers. The search has proved very successful, with a range of such materials showing laser action, both flash-lamp pumped and cw pumped by a Kr ion laser. Tuning is typically in the range ∿ 750 - 850 nm. Materials include $Cr:KZnF_3$[17], Cr:GSAG[18], Cr:GSGG[19] and $Cr:ZnWO_4$[19]. The essential feature of these materials is that the chromium ion must be in a site with a weak crystal field[20-22], thus enabling laser action to take place on the $^4T_2$ - $^4A_2$ transition as a tunable, quasi-4-level system. In a strong crystal field, such as for Cr^{3+} in ruby, the excited population is mostly in the ^2E level, leading to narrow-line (i.e. non tunable) 3-level laser action via the ^2E - $^4A_2$ transition[22]. Performance figures include the following: a room temperature cw laser based on $Cr:KZnF_3$ and Cr:GSAG pumped by a Kr ion laser has given tuning from 780 - 865 nm and 735 - 820 nm, respectively[17] with up to 50 mw output for 1 w of absorbed power. Such a performance offers immediate competition with near infrared dye lasers. Flashlamp-pumped operation of Cr doped materials (other than alexandrite) has had mixed success so far with some problems of colour centre formation initially encountered. Recently reported results[23] for Cr:GSAG are ∿ 200 mJ output (in the free running mode) for ∿ 140J input, with a slope efficiency of 0.24%.

With weaker crystal field the wavelength of the $^4T_2$ - $^4A_2$ emission gets longer. For example $Cr^{3+}:ZnWO_4$ has shown laser action around 1 μm[24]. This indicates one possible approach to providing tunable wavelength cover of the range ∿ 0.9 - 1.1 μm. However an alternative approach is now available in the form of material with quite remarkable tuning properties. This is titanium-doped sapphire $Ti^{3+}:Al_2O_3$, first reported as a laser material by Moulton[25,26]. The tuning range covered by this material extends from 0.66 μm to 1.04 μm[27]. Pump bands are broad, allowing cw pumping by Ar laser, pulsed pumping by the second harmonic of a Q-switched YAG laser, and flash lamp pumping. cw pumping has yielded a threshold of 2.4 w, with 1.6 w output for 12 w input[28]. The relatively high threshold is a consequence of the extremely broad tuning since (at least, for small linewidths) the threshold is directly proportional to the linewidth. The extremely wide tuning range and high efficiency of $Ti:Al_2O_3$, both under cw and pulse pumped conditions suggest that dye lasers are about to face some severe competition.

Diode-laser pumped Nd lasers

Soon after the invention of GaAs luminescent diodes and diode lasers these devices were being applied to pumping of solid state lasers, such as $Dy^{2+}:CaF_2$[29] and $U^{3+}:CaF_2$[30]. The good match between the GaAs laser emission and pump bands in NdYAG at ∿ 0.8 μm, was noticed early and Ross[2] reported the first results for a Nd:YAG laser pumped by a GaAs diode laser. Over the years various authors have reported results for this combination of pump and laser, with results steadily improving as GaAs devices have improved. In the past few years, with the ready availability of GaAs diode lasers with powers in the tens of milliwatts to hundred of milliwatts range, giving good beam quality, room temperature operation and good reliability, the interest in diode-pumped NdYAG lasers has suddenly blossomed. Attractions of such lasers are the fact that they are compact, efficient, reliable, can be readily operated in a single frequency and TEM_{00} mode and can have excellent frequency stability.

Some examples of the performance figures to date include the following: 80 mw cw output from a NdYAG laser pumped by a 200 mW GaAlAs diode array, with only 1 watt of electrical input power[31]: frequency stability of 10 kHz over a 0.3 sec period[32]: efficient intracavity harmonic generation in a diode pumped NdYAG laser, with 11 mw of green output at 0.53 µm for 1 w of electrical input to the diode array[33].

The ease with which single mode operation can be achieved in the very short cavity of such NdYAG lasers[32], has provided a convenient means for achieving single frequency operation in high power NdYAG lasers, by injection seeding[34]. Other interesting demonstrations include gain-switching of the NdYAG laser by modulating the GaAs pumping pulse[35], Q-switched and modelocked operation of diode-pumped NdYAG lasers[36], operation at 1.3 µm on the $^4F_{3/2}$ - $^4I_{13/2}$ transition[37], and operation of NdYLF pumped by a diode laser[38].

Clearly with increasing diode laser powers becoming available at decreasing prices, the use of such NdYAG lasers can be expected to grow rapidly.

Fibre Lasers

The first demonstrations of lasing in optical fibres were made on multimode fibres pumped transversely by incoherent sources[3,39]. Over the years since then a small amount of work has continued on fibre lasers, with some advances being made, such as end pumping of fibres[40], and pumping of fibres by a diode laser[41]. All of this work had involved multimode fibres with core diameters of typically tens of microns to hundreds of microns. A break-through was recently made with the development of a technique[4] for fabricating single-mode fibres (with core diameters of typically 5 µm) doped with rare-earth impurities, but with very low losses characteristic of silica fibre used in optical communications. The fabrication technique can be applied quite generally to allow various dopants to be incorporated into the core. Initial work[4] was based on Nd doped fibre, but more recently Er doped fibres have lased successfully, operating at 1.55 µm[11]. Attractive features of fibre lasers include the low threshold, the freedom from thermal distortion problems, the availability of broad gain profiles so that tuning can be achieved, and ultimately so that short pulse generation may be achieved in a mode-locked system. Thus in many ways fibre lasers present features available in dye lasers but with additional advantages such as the ability to Q-switch[42], the long term stability of the laser medium, the compact configuration and the absence of cooling requirements. The low threshold makes diode laser pumping particularly attractive[9].

Some of the results achieved since the first single mode fibres were fabricated include the following:

Q-switched operation with peak power levels of several watts[42];
Mode-locked operation using an active mode locker[43];
Efficiencies of 30%[9];
Widely tunable operation, using either a grating tuner[44] or birefringent filter[45]. Tuning ranges of 0.900 - 0.945 µm and 1.070 - 1.135 µm were observed[45] on respectively the $^4F_{3/2}$ - $^4I_{9/2}$ and $^4F_{3/2}$ - $^4I_{11/2}$ transitions of Nd^{3+};
Low threshold cw operation on three-level transitions, such as[11] $^4I_{13/2}$ - $^4I_{15/2}$ in Er^3 and[10] $^4F_{3/2}$ - $^4I_{9/2}$ in Nd^{3+}.

These are very early days for the monomode fibre laser but already they have shown an impressive range of capabilities. The low thresholds obtained so far suggest that other transitions, which have not previously been demonstrated in bulk glass systems could prove to work efficiently in a fibre geometry. Also, whereas most of the experiments reported above have used non-fibre components for such items as mirrors, filters, Q-switches and modulators, future directions of development will include replacing these components by fibre devices so that an all fibre construction can eventually be realised, with its consequent advantages of compactness and reliability. An example of this type of progress is given by the use of an optical fibre coupler to provide feedback in the form of a ring resonator rather than using mirrors[44].

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