ADVANCES IN LASERS AND APPLICATIONS

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ADVANCES IN LASERS AND APPLICATIONS

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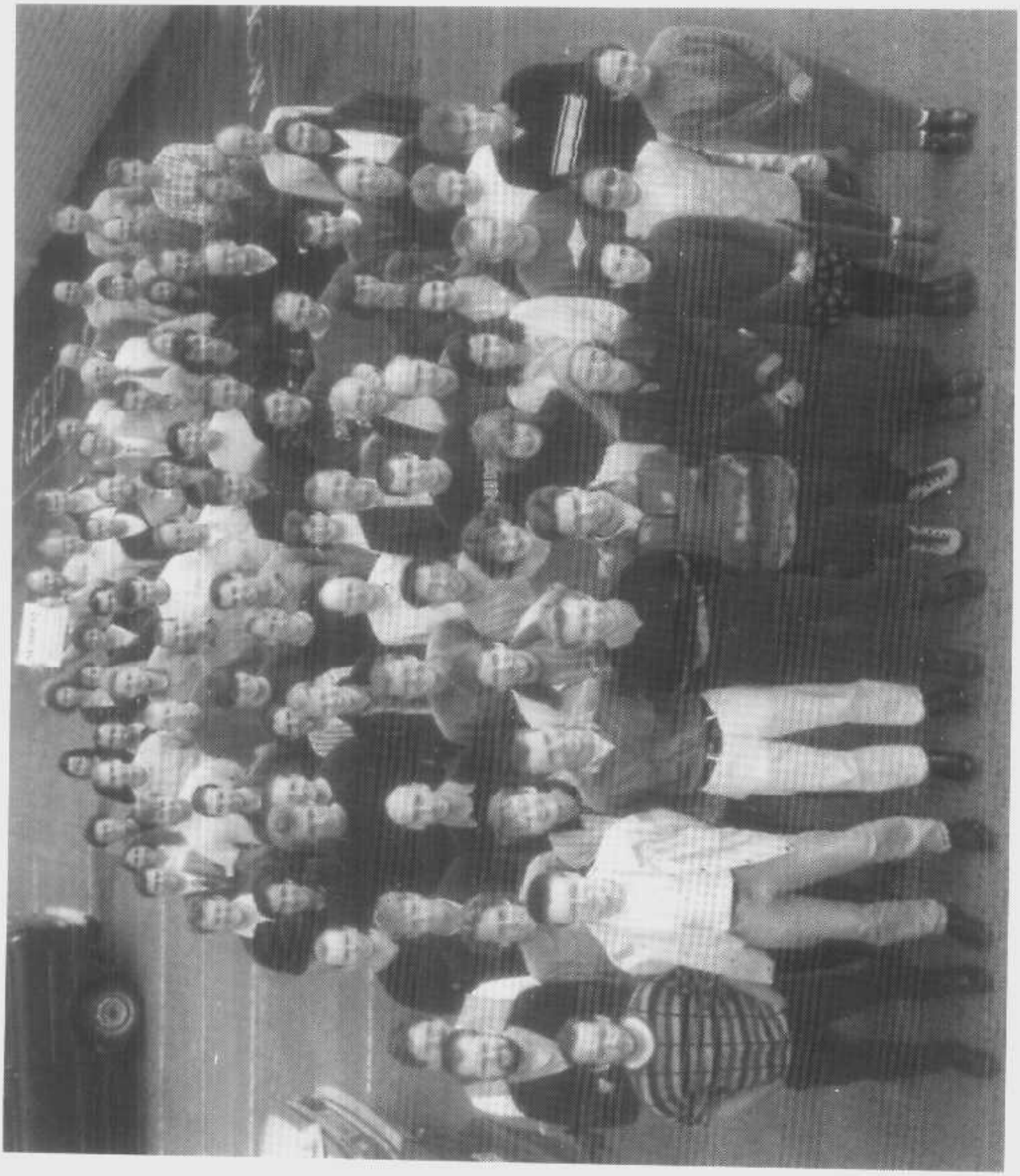

Director's Preface

The last decade or so has seen a renaissance in the field of lasers. Diode-laser-pumped solid-state lasers have been taking a larger and larger share of research activities, and then of commercial devices. At the same time there have been major advances in the generation of ultrashort pulses, and in the materials and techniques used in optical parametric oscillators. The advances in each of these three fields have helped the others become stronger, and have allowed the development of a wide range of real-world applications.

This book is written as the proceedings of the 52nd Scottish Universities Summer School in Physics. This was a nine-day international summer school organised to run immediately before two major international conferences in this field in Glasgow. The School took as its topic "Advances in Lasers and Applications", with the emphasis being on the science and applications of solid-state lasers, optical parametric oscillators and amplifiers, and ultrashort pulse lasers. An outstanding team of international experts came to the University of St Andrews to give their presentations and to discuss their ideas with all the participants.

Although this book forms the proceedings of the School, I see it more importantly as an up-to-date review of the science, technology, and applications of modern laser systems. It will be of wide interest to scientists and engineers working with lasers and their applications. Each chapter is written by a distinguished expert as a tutorial review of their field, and covers some of the major topics that were explored at the School. As such, the chapters are suitable as introductions to the various specialist areas at a postgraduate level and beyond. I believe they will be particularly valuable in allowing experienced people in one field to learn more about relevant developments in other topics. The chapters assume a basic knowledge of lasers and nonlinear optics.

The 52nd SUSSP was held at the University of St Andrews from the 5th to the 13th of September 1998. Accommodation was in John Burnet Hall, and the formal programme was at the School of Physics and Astronomy. The 100 participants from 16 countries were able to attend the 35 lectures presented by 18 senior scientists. Most of the "young researchers" also presented their own work orally or in one of the two poster sessions. The School succeeded in bringing people together to share their knowledge and ideas in a spirit of co-operation. The following week many of the participants went on to attend the associated CLEO/Europe – EQEC conferences in Glasgow.

As well as the formal events, a busy social programme helped keep people together at the School. Putting and football competitions gave some exercise, while others explored Scott's ship Discovery. Participants were able to take an organised hike up into the Ochil hills, and many took the opportunity of walks along the St Andrews beaches. The many pubs in St Andrews encouraged toasts to be drunk to new friends. Food, drink, and music from around the world were enjoyed during the international evening, and the banquet and ceilidh on the final evening gave a Scottish flavour and brought the proceedings to a pleasant close.

The director and other organisers are grateful for the help of many organisations and individuals in the running of the School. The School was run with financial and organisational support from SUSSP. The principal financial sponsor was the European Commission through the TMR and INCO programmes, but significant financial assistance was also provided by the UK EPSRC, the Quantum Electronics Group of the UK Institute of Physics, LEOS, OSA, Elliot Scientific, and Scottish Enterprise. The Director and all participants greatly appreciated the sterling work of the local organising team, Dr Kishan Dholakia as the School secretary, Dr Derryck Reid as treasurer, Ms Tracy McKechnie as social organiser, and Professor Alan Miller for his advice and encouragement.

The concept of the School was first mooted by Professor Terry King as chairman of the Quantum Electronics Group of the IOP, and then taken further by the members of the local organising committee of CLEO/Europe - EQEC. Thanks are due to them and to the members of our International and UK Advisory Committees who helped the local team bring forward the successful proposal for the School. Professor Jim Hough and Dr Robin Vaughan provided valuable input to the bursaries committee. Staff and students of the School of Physics and Astronomy cheerfully gave their support to the Summer School, willingly assisting its running in many ways. Jackie Smith and her team at John Burnet Hall provided an excellent residential service.

We thank our team of lecturers for giving a series of great presentations, and for willingly sharing their time with others during their stay in St Andrews. We are also grateful to all the young researchers for providing the enthusiasm, energy, and team spirit that were hallmarks of the School.

Bruce Sinclair

St Andrews, March 1999

Editors' Note

The editors would like to thank all the authors for their excellent and timely contributions to this volume, and for the very considerable time and effort they expended in the production of their manuscripts. Michael Mazilu is acknowledged for his expert help in handling the many different submitted file types and converting them into the LaTex format of the final version.

David Finlayson and Bruce Sinclair

St Andrews, March 1999

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Contents

A review of diode-pumped lasers

D C Hanna and W A Clarkson

University of Southampton,England

1 Introduction

The first demonstration of a diode-pumped laser was in 1964 (Keyes and Quist 1964), just two years after the first operation of a diode laser. Potential attractions of diode pumping, compared with pumping by an incandescent lamp, were evident at that time. However, it needed about 20 years before diode lasers became commercially available with long life under room-temperature operating conditions and with the power levels appropriate for laser pumping. Pioneering experiments performed using such diode lasers as pumps graphically illustrated the benefits of diode-pumping and were discussed in an early review paper (Byer 1988). These benefits include high efficiency, compactness, stable low-noise operation, reduced thermal effects in the laser medium, long-life and the prospect, if not an immediate benefit, of low cost. Decreasing costs of diode lasers and increasing diode powers have gone hand-in-hand and so fuelled this interest in diode-pumped lasers. As these trends continue, so there is an inexorable move towards diode-pumped lasers of ever greater power. The earlier prevailing notion that diode-pumped lasers are free from pump-induced thermal effects, has long gone. That was, to some extent, a consequence of the low diode powers initially available. Now, with diode lasers offering tens of Watts of pump power, thermal problems have become a key issue in the further development of diode-pumped lasers.

This question of thermal problems will form an important theme of this brief tutorial review (Section 3). First however (in Section 2), we will briefly consider the question of appropriate geometries (pumping configuration, shape of laser medium, resonator geometry) for diode-pumped solid-state lasers. In fact there is now a bewildering variety of geometries under investigation, with many being commercially available, each with its staunch champions. Clearly the optimum choice of geometry is far from being a settled question. In fact, it is interesting to note that two of the currently favoured geometries, namely the fibre laser and the face-pumped thin disc laser, represent two diametrically opposed extremes from a basic cylindrical rod geometry. With such widely divergent approaches, it is clear that there is still considerable scope for innovative ideas in this area and even relatively small changes in, for example, the available brightness or power of diode lasers, could have major consequences in terms of changing the balance between favoured geometries, or indeed, stimulating the invention of yet more contenders.

2 Choice of geometry

2.1 Longitudinal or transverse pumping

It is useful, in order to have a framework for subsequent discussion, if we first consider a laser medium having the form of a cylindrical rod, with resonator mirrors placed at each end of the rod (Figure 1). Two widely used pumping configurations are longitudinal-pumping (also known as end-pumping), and transverse-pumping (also known as side-pumping.) Heat removal is from the lateral surface of the cylinder, so the heat flow is radial (hence two-dimensional). As we shall see in more detail in Section 3 (see also Koechner 1996) this radial symmetry for the heat flow has some undesirable consequences. It leads to a radial symmetry of stress (arising from the radial temperature gradient), and hence a radial symmetry of the stress-induced birefringence. Thus, in an otherwise isotropic medium, the effect of this birefringence on the polarisation state of the laser beam passing through the rod is to produce a complex depolarisation behaviour, equivalent to the effect of retardation plates having a radially dependent value of retardation and with axes oriented in radial/tangential directions. The resulting depolarisation can cause significant loss and indeed be the barrier to further power scaling. A means of reducing the effect of this depolarisation is indicated in Section 3.

Another solution to the birefringence problems is to use a slab-shaped laser medium, and arrange for a one-dimensional heat removal (Figure 2) from the large faces of the slab. This means that the thermally-induced birefringence properties of the slab correspond to a retardation plate which is everywhere oriented in the same direction even though the magnitude of retardation varies with location along the direction of heat flow. The problems associated with the complex depolarisation behaviour of the rod are eliminated. Notice that for the slab there are two versions of transverse-pumping, either edge-pumping, that is through the small side of the slab, or face-pumping through the large face(s). That

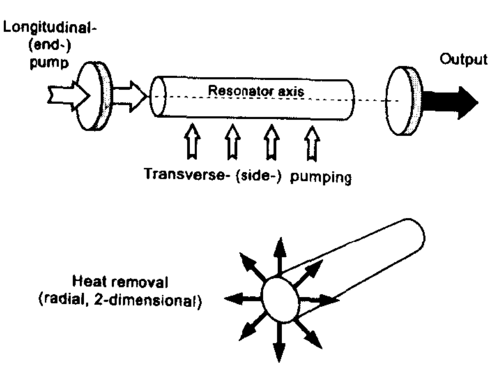

Figure 1. *Cylindrical rod geometry.*

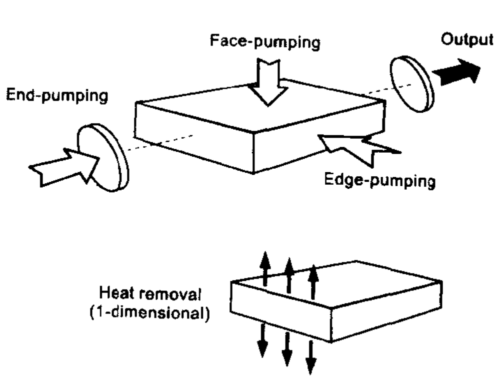

Figure 2. *Planar slab geometry*

choice can depend on whether the pump absorption is adequate in the short dimension perpendicular to the face, whether the pump can be focussed into the small dimension of the edge, and whether the arrangements for heat removal, which ideally should be from the large face, are compatible with face-pumping.

2.2 Rod-lasers with longitudinal pumping

Longitudinal pumping (see Figures 1 and 2) avoids the problem of conflicting arrangements for pumping and heat removal. It has a number of other attractive features (and, as we shall see below, it also has its problems). Attractions are: (1) It can provide a long absorption path in the medium, thus helping to achieve efficient pump absorption. A longer length also reduces the heat load per unit length, thus reducing the risk of stress-induced fracture. (2) By reducing the transverse dimension of the pump beam, the gain for a given pump power can be increased and thus significantly higher gains can be achieved. For low gain laser transitions, or 3-level (and quasi-3-level) transitions where a high pump intensity is needed, longitudinal pumping is particularly valuable. (3) With a pump beam of small transverse dimensions, one can conveniently match the laser mode-size to the dimension of the pumped volume. This is helpful for selection of the lowest-order transverse mode and is also conducive to the attainment of a high conversion efficiency from pump light to laser light.

Of course there are limits to how small the transverse dimension of the pump beam can be, imposed by diffraction spread over the length of the medium (or over the pump extinction length, whichever is the shorter). Most diode lasers do not have a diffraction limited output. Their divergence is (approximately) M^2 that from a diffraction limited source, where the pump beam quality factor M^2 can be up to about 1000 (see Sasnett (1989) for a discussion of M^2). The minimum effective pump beam radius (defined as r.m.s. beam radius which results in the minimum pumped volume) is given by (Clarkson and Hanna 1998).

$$w_{p_{\min}}^2 = \frac{2\,\lambda\,M^2}{\alpha_p\,\pi\,n\sqrt{3}} \tag{1}$$

where α_p is the pump absorption coefficient, λ is the pump wavelength, and n is the refractive index of the laser medium. So, the pump beam area is proportional to M^2, and hence the threshold pump power is inversely proportional to M^2. Pump sources with a small value of M^2 are therefore desirable for end-pumping, particularly for pumping low-gain transitions. Later, we make a brief mention of shaping the highly elliptical output beam from a diode-bar, so as to achieve an essentially circular beam with a minimised M^2 value. Even so, the M^2 values achieved in this way are typically about 80. It is important to bear in mind these large M^2 values when extrapolating from the results obtained using a Ti:sapphire laser ($M^2 \sim 1$ typically) as a simulation of pumping by a diode-laser.

We have indicated that longitudinal pumping has a number of benefits. However, the more intense pumping also brings its own problems. For example, the thermal lensing can be very strong. If the lens was equivalent to a spherical lens then this could, in principle, be corrected by an appropriate choice of spherical mirrors or lenses in the laser resonator. It has to be recognised however, that this lens power will change with pump power. A number of papers by Magni and co-authors (see e.g. Magni 1986a,b; Magni and Zavelani-Rossi 1998) indicate how optimised resonator designs can be made. The thermal lens is incorporated in these designs which provide optimal resonator stability with respect to misalignment sensitivity and to changes of thermal lens power. The assumption made in these papers is of a spherical lensing behaviour in the laser rod. This is valid for a laser medium that is subjected to a transversely uniform pump intensity (typical of lamp pumping, and transverse pumping in general) and which would apply to end-pumping with a uniform ('top-hat') pump beam. In fact, however, pump beams typically have a Gaussian-like pump intensity distribution. This leads to a lensing behaviour with a significant non-spherical component, that is, the lens has spherical aberration. This aberration can lead to a major degradation in the M^2 value of the output beam of the diode -pumped laser.(Clarkson and Hanna 1998). In Section 3 we indicate an approach that mitigates this problem by choosing a suitable resonator design, and that has proved satisfactory (giving $M^2 \sim 1$) for end-pumped lasers of multiwatt power. For much higher powers, transverse pumping with careful attention to pump uniformity has proved very effective at power levels up about 200W (Hirano *et al.* 1998).

So far we have not given any indication of how laser material parameters enter into the design choices. This is a complex question as it involves a multi-parameter design space and we do not attempt to provide any general conclusions. We will briefly indicate some of the factors that need to be considered in practice. Thus, for example, if we go back to Equation (1), we note that a small M^2 value is beneficial in reducing the threshold power. However, even if M^2 is larger than desirable, there may be the possibility of choosing a material with a strong pump absorption (large α_p), thus still allowing a reasonably small pump spot-size to be used. The crystal $NdYVO_4$ provides a good example of the use of this strategy. It has a strong pump absorption and also has a very high gain cross-section, so that an acceptable gain can be achieved even when pumped by diodes whose output has a large M^2 (for example, after having been fibre-coupled). Absorption of pump light in a shorter length does however pose an increased challenge in terms of thermally-induced stress fracture. Other material parameters that determine how close one is to the stress fracture limit are the material tensile strength and the thermal conductivity. Thus one can see already how many material parameters begin to enter the design process. As $NdYVO_4$ is naturally birefringent, it does not suffer problems from thermally-induced stress birefringence since the overall birefringence is dominated by the material's intrinsic birefringence. $NdYVO_4$ is not, however, immune from thermally-induced lensing, which depends on thermal conductivity and the temperature coefficient of refractive index, dn/dT.

Thermal inputs depend on other factors also. For example, in Nd-doped materials there is an upconversion process involving two neighbouring Nd ions in the upper laser level which leads to one of these ions being de-excited and the energy thus lost being deposited as heat (e.g. Guy *et al.* 1998, Pollnau *et al.* 1998). This is more problematic in highly doped material, and is obviously more of a problem for end-pumped lasers because of the high inversion density. This effect is clearly seen as a degradation in performance under Q-switched conditions or in operation as an amplifier, as in both thee cases the inversion density is at a higher level than in cw operation.

So the catalogue of relevant material parameters increases, even though we have so far restricted this discussion to Nd laser transitions (We note here the valuable compilation of laser material parameters in Moulton (1987) and in Zayhowski (1997)). Other transitions, such as those of Yb offer significant differences, some beneficial, some not. Thus the Yb:YAG laser (and other Yb-doped materials) are currently exciting considerable interest. A primary initial motivation was that in Yb:YAG the energy difference between pump laser photons (at ~940nm) and the emitted laser photons (~1030nm) is about one-third of that between pump photons (807nm) and emitted photons for the most common laser transition in Nd:YAG at 1064nm. This represents a reduction of heat load by a factor of three, and so Yb:YAG presents an effective way of reducing the magnitude of the pump-induced thermal effects. Other significant differences are that the absorption and emission cross-sections are smaller than for Nd:YAG, but on the other hand, this can be offset by the fact that much higher Yb concentration can be used as the simple Yb^{3+} energy level structure does not allow the concentration-quenching mechanism that is present in Nd-doped materials. Finally it should be added that the lower laser level in Yb is significantly populated at room temperature (~5%), so that more intense pumping is needed to achieve net gain. Thus there are many factors different from Nd:YAG and there is no single universal statement that can be made along the lines that one system is better than the other. The relative merits are very much dependent on the intended operating conditions. Furthermore, the balance could be shifted significantly by other changes, such as improvements and developments in diode laser performance which may arise in a different manner for 807nm diodes for Nd pumping compared with 940nm diodes for Yb pumping.

2.3 Face-pumped thin disc lasers

The differences between Nd:YAG and Yb:YAG have been instrumental in bringing about a new design approach to high-power diode-pumped lasers. This is the face-pumped thin disc geometry, (Figure 3), which has been applied to such good effect with Yb:YAG (Giesen *et al.* 1994), in which one starts with the benefit of a smaller pump quantum defect. The basis of this approach is to avoid transverse thermal gradients by removing heat from the face of a thin disc rather than, as in the case of a cylindrical rod, from its transverse surface. By keeping the disc thin, the temperature difference between the cooled face and the pump input face is kept small, thus minimising any increase in thermal population of the lower laser level. The thin disc results in a weak pump absorption. To some extent, this can be offset by the higher concentration possible for Yb, but a multipass pump arrangement is needed to obtain reasonable pump efficiency. This completely new geometry has necessitated a series of technological developments to cope with features which are so different from the conventional geometries. The result however, is that a level of performance is now achieved (Erhard *et al.* 1999) which clearly shows the benefits of circumventing the thermal problems of Nd:YAG in a conventional rod geometry.

2.4 Fibre lasers

The thin disc laser can be viewed as a very short laser rod. The other extreme, of an extremely elongated laser rod is represented by the fibre laser. We give only a brief discussion of fibre lasers here, as they are covered in a separate chapter of this volume (Tropper 1999). The main points about fibre lasers that we wish to emphasise in this context are the dramatic move towards higher power operation (many tens of Watts

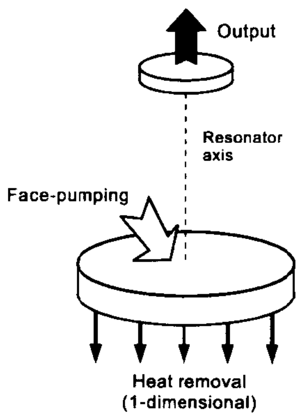

Figure 3. *Face-pumped thin disc geometry, with heat removal from the back face.*

already reported), and the added design flexibility that is conferred by virtue of the fact that very high gains are available, so that master-oscillator power-amplifier (MOPA) designs become particularly attractive.

An essential feature of the fibre laser is that the active (rare-earth) ion is doped into a guiding core (Figure 4). This is usually chosen to have a diameter of a few micrometres, so that the fibre is monomode, that is, at the laser wavelength only the lowest order mode can propagate. Problems of transverse mode control, which are characteristic of bulk lasers, are thus removed. Likewise problems of heat dissipation are removed, since heat can be dissipated over a long length of fibre, and in any case the heat has only a short distance to travel to the outer surface of the fibre. Two of the main obstacles to high-power operation with good beam quality, that are encountered with bulk lasers, are thus removed. On the other hand two new problems enter. One concerns the power limitation imposed by damage or other nonlinear limiting mechanisms, as high-powers propagate through the very small core area. The other problem is a more basic one - if a high output power is to be achieved then a high input power is required, and in this case into a monomode core of small dimensions. If end-launching into the core is used then the pump laser has to have an essentially diffraction-limited beam. However, high-power pump lasers such as diode lasers are typically a long way from being diffraction-limited.

The solution to this problem has been via the use of cladding-pumping (e.g. Po *et al.* 1993), see Figure 4, in which the pump light is launched into the cladding, either at the end, or through the side, in which case multiple pumps can be used along the fibre. Light which is launched into the cladding is guided by the interface between the cladding and its outer cladding and thus gets progressively absorbed into the core as it propagates. The result is a monomode laser output from the core, and since pump powers of many tens of Watts can be launched in this way, then tens of Watts of output is achievable, with a beam quality factor M^2 of essentially unity. Such schemes will undoubtedly have many important consequences for the future development of coherent light sources, and it will take some time for these consequences to be worked through. So far there has been relatively little published on the question of scaling limitations to fibre lasers (see however Zenteno 1993), and it is clear that much work will be needed to fully characterise these high-power fibre lasers.