Eur. Phys. J. Special Topics **224**, 2529–2543 (2015)

DOI: 10.1140/epjst/e2015-02562-0

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

Progress in high average power ultrafast lasers

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Received 17 December 2014 / Received in final form 31 August 2015
Published online 26 October 2015

Abstract. The impact of femtosecond lasers across science and engineering has been significant. The one area which has so far proved hard to access for femtosecond lasers has been the combination of high peak power and high average power. This review seeks to highlight the issues which make high average power hard to achieve in many femtosecond systems, and looks at the routes that are now being taken to achieve the goal of high peak and high average power.

1 Introduction

Pulsed lasers have, since their first demonstration [1], provided an important route to new science. Both the time resolution and the high intensities available from pulsed lasers have proved critical in new discoveries, and in new technological applications. The progress in reduction of pulse length and increase of peak intensity as the laser has been developed is spectacular, with pulse durations available from laser-based sources reducing from microseconds to attoseconds [2] over the course of about 40 years, and intensities rising from a few kW cm^{-2} to greater than 10^{22} W cm^{-2} [3]. The parallel between the rise in intensity and reduction in optical pulse length is also striking, showing an inverse linear dependence in experimental results over 15 orders of magnitude [4].

Equally striking is the change in average power between the pulsed ruby lasers of the early 1960s and the Ti:Sapphire femtosecond lasers of today. Early ruby lasers had average powers in the region of tens of milliwatts to watts. A typical commercial regenerative amplifier based Ti:Sapphire laser system producing 30 fs, mJ level pulses found in research labs today has an average power of a few watts. This review article looks at the underlying science behind the relatively low average powers of many modern ultrafast lasers, and reviews the progress toward the goal of ultrafast lasers with kilowatt average powers and petawatt peak powers.

2 Managing thermal and nonlinear effects

The technological problems involved in producing high average power lasers and high peak power lasers are significantly different. In a high average power laser system, the principal problem is managing the thermal load within the laser, because any

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difference between the power used to pump the laser and the optical output power of the laser will typically be deposited as heat somewhere within the laser system. In the case of high peak power pulsed lasers, the principal challenge is to manage the optical nonlinearity inherent in the propagation of high peak power pulses through optical media. Solutions to these two challenges have shaped the design of modern high power and ultrafast lasers.

A secondary and related challenge for all laser systems is the efficiency with which the laser power can be produced. Most high pulse energy lasers are optically pumped, using either flashlamps or semiconductor laser diodes to provide the pump photons. Flashlamps can be efficient ($\sim$50%) in terms of electrical to optical power conversion, but their light output is often spectrally broad and spatially dispersed, meaning conversion of electrical power to laser output power using flashlamps is generally low; commercial flashlamp-pumped Nd:YAG lasers typically have wallplug efficiencies of a few percent. Laser diodes have high electrical to optical conversion efficiencies, closer to $\sim$70%, and their output is spectrally much narrower and spatially much better collimated than that of flashlamps, meaning that pumping efficiencies can be very high for diode-pumped solid state lasers; often above 20%. Actual efficiency will also depend on the difference in wavelength between pump and probe, the quantum defect, which provides an upper limit on efficiency in any optical pumping scheme.

2.1 Thermal effects

In an optically-pumped solid state laser, the difference in energy between pump and output photons is deposited as heat within the laser medium. Any absorption due to defects or impurities within the laser medium can also cause absorption of the pump. All of these will change the temperature distribution within the laser medium, and hence cause a change in the spatial refractive index distribution. This will distort the optical path within the laser cavity. Management of the temperature distribution within a laser medium is central to the successful operation of high average power lasers.

Several factors can reduce the change in temperature distribution within the laser medium caused by optical pumping. The quantum defect clearly plays a large role; for example, in Ti^{3+} -doped sapphire pumped at 530 nm and lasing around 800 nm, 33% of the pump energy is deposited as heat, whereas for Yb^{3+} -doped optical fibres pumped at 975 nm and lasing at 1050 nm, only 7%of the pump power is deposited as heat. Hence many high average power lasers use optical centres with very small quantum defects – Yb^{3+} being the most common. The Yb^{3+} system is quasi-four level, and has a very simple level structure – two electronic states, each broadened into Stark multiplets. The small quantum defect presents a disadvantage in that an increase in temperature of the host material will populate more of the upper Stark levels in the ground state, resulting in absorption at the laser wavelength.

The thermal conductivity of the laser material has a significant influence on temperature distribution, with high thermal conductivity media able to remove heat more effectively from within a large volume. However, choice of laser medium is often dictated by properties other than thermal conductivity. It is possible to increase thermal conductivity significantly in many laser media by cooling to much lower temperatures. In crystalline materials, as the temperature is lowered, the thermal conductivity increases, thermal expansion coefficients are reduced, and thermo-optic coefficient, dn/dT, is reduced, all of which lead to a decrease in both direct temperature-induced optical distortions and stress-induced optical distortions. In sapphire, these effects lead to reductions by factors of 200 and 450 in direct and stress-induced distortions when the temperature is reduced from 300 K to 77 K [5], and similar effects are seen in other hosts such as YAG [6]. Glass hosts, however, do not show the same positive effects in these coefficients with decreasing temperature, because of the very different nature of the vibrational properties of glass compared to crystals [7]. The thermal conductivity of fused silica glass reduces as temperature is reduced; opposite behaviour to that seen in crystalline hosts. On cooling, laser ions in solid host materials also show changes to their absorption and emission properties, which have both good and bad connotations for performance: absorption cross-sections can increase [8], but the transition line widths and shapes can change quite dramatically [9,10]. In particular, absorption and emission lines always get narrower at low temperatures, which is a particular concern for potential ultrafast pulse generation.

If both quantum defect and thermal conductivity are optimum, the final route to controllable temperature distribution is choice of laser geometry. The geometry of early lasers, in which the medium is a rod placed along the axis of the laser cavity, is very susceptible to formation of thermally-induced lenses because the peak of the heat deposition is along the centre axis of the rod. Thus heat flow out of the crystal is toward the surface of the rod, forming a radial temperature distribution, and a thermal lens. Effective high average power lasers require reduction or removal of thermal lensing. This can be achieved using different geometries, reducing the effective dimensionality of the gain medium in order to increase surface/volume ratio and aid heat removal.

2.2 Nonlinear effects

The development of ultrafast lasers with high pulse energies relies on management of the very high peak powers of the pulses, which produce nonlinear propagation effects as the pulse travels through the laser medium. Very high peak powers can cause complex spatiotemporal distortions of the pulse, and can lead to catastrophic damage of the laser medium.

The principal means of management of high peak powers is to reduce them by spreading the pulse in either space or time. Spatial spreading of the beam is straightforward but limited by several factors – a large increase in gain medium transverse size makes the removal of heat from the centre of the beam more difficult, exacerbating the thermal problems described in 2.1. In addition, amplified spontaneous emission or lasing can build up transversely within the gain media, adversely affecting performance [11]. Decreasing peak pulse power by spreading the pulse temporally was first demonstrated in 1985 [12] by Strickland and Mourou. The technique relies on positive and negatively dispersive delay lines used before and after pulse amplification, temporally stretching the pulse via second order dispersion by factors of up to $\sim 10^6$ to reduce the peak power reached during amplification. This technique, known as chirped pulse amplification (CPA), is now universally used in high pulse energy laser systems. In modern systems, grating-based stretchers and compressors are used, and the ability to increase the beam diameter after amplification to very large values allows peak powers above a petawatt to be used in CPA with very large gratings. As an example, the compressor on the Vulcan Petawatt laser at the Rutherford Appleton labs, UK, uses a beam diameter of 600 mm, and compressor gratings of 940 mm diameter, bringing the flux on the gratings down below the damage threshold and delivering 500 J pulses of duration 500 fs onto a target. The degree of stretching needed to reduce peak pulse intensities to a manageable level is dependent on the nonlinear phase shift acquired as the pulse propagates through the laser medium. The nonlinear phase shift, B, is given by:

$$B = \frac{2\pi}{\lambda} \int n_2 I(t,z) dz \tag{1}$$

where n_2 is the nonlinear refractive index, and $I(t,z)$ is the intensity of the pulse. As the pulse is strongly chirped, time variation in phase is mapped to spectral phase variation, so that significant nonlinearity in propagation will prevent compression back to the original pulse length. The nonlinear phase shift in an amplifier is parameterised by the *B integral*, given by Eq. (1). The peak value of the B integral must be kept small for undistorted pulse amplification, with values not much greater than unity [13].

The physical limits to CPA are imposed by the size and precision of the optical systems used for stretching and compression. The space available in a typical lab imposes an upper limit on compressor size of around 2 metres. The possible time delay between different spectral components within a pulse is then limited to difference in paths through the compressor, which is limited approximately by its physical size. Thus stretching to more than a few nanoseconds duration is not common. Techniques to produce further temporal stretching beyond that available from CPA, such as divided pulse amplification (DPA) [14], will be discussed later in the context of optical fibre amplifiers.

3 State of the art in Ti:Sapphire lasers

The most common ultrafast laser in use at present is based on titanium-doped sapphire. Femtosecond pulses are available from Ti^{3+}:sapphire oscillators via Kerr lens mode locking (KLM) [15], a simple and effective process requiring much less complexity than previous generations of mode locked ultrafast lasers. The gain bandwidth of Ti^{3+}:sapphire is ~ 100 THz, centred around 800 nm, potentially supporting pulses shorter than 10 fs. Sapphire also has very high thermal conductivity, allowing better conduction of heat away from the centre of the laser rod and lower thermal gradients. Sapphire is also very hard, and thus has high damage thresholds.

At the time of writing, typical commercial Ti^{3+}:sapphire-based ultrafast laser oscillator/amplifier systems are limited to average output powers of 20–30 W. This limit is imposed by the ability to control thermal distortions in the laser rods. The rods are cooled to around 77 K to achieve this performance. Usually this power is approximately constant as the pulse energy is increased, so performance of 20 mJ/1 kHz or 2 mJ/10 kHz are possible, although technical complexities increase as the pulse energy increases. These systems are often pumped by diode-pumped, Q-switched Nd:YAG or Nd:YLF lasers, frequency-doubled to reach an appropriate photon energy to be absorbed by Ti^{3+}:sapphire. Typically as the pulse energy increases above a few tens of millijoules, the repetition rate decreases dramatically, reducing average power significantly, so that most petawatt level systems have repetition rates of a few pulses per hour. Possibly the most impressive combination of high peak and high average power at the time of writing is the BELLA laser at Berkeley [16]. This laser, a commercial system produced by Thales Optronique SA, is capable of pulses of 40 J at a repetition rate of 1 kHz – an average power of 40 W. The BELLA system is pumped by flashlamp-pumped doubled Nd:YAG lasers, hence the wallplug efficiency is very low – of order 0.03%. Efforts to improve the average power of pulsed Ti^{3+}:sapphire systems include the TISA-TD project currently funded under the EU's FP7 programme. This project aims to use Ti^{3+}:sapphire in a thin disk geometry, with the Ti^{3+}:sapphire disks cooled on the faces by transparent diamond heat spreaders. Pumping is by doubled thin disk Yb^{3+}: YAG lasers.The target performance is 200 W average power, with 20 mJ pulses at a repetition rate of 10 kHz – an order of magnitude higher than currently-available systems.

4 Ultrafast slab and thin disk lasers

Reduction of thermal distortions in high average power lasers is usually performed by increasing surface/volume ratio of the gain medium. This can be done in several geometries, whose advantages and drawbacks will be considered in this review. Forming the gain medium into a thin layer allows a significant improvement in thermal properties and can be used within a laser cavity in several ways. The most common are slab lasers, in which the cavity mode propagates along one of the long dimensions of the gain medium, and disk lasers, in which the cavity mode propagates along the short dimension.

4.1 Slab lasers

Forming the gain medium into a thin slab is a simple way of controlling thermal gradients in the beam. For high average power operation, heat can be removed very effectively from the large faces of the gain medium if the system is pumped from the edges, and edge pumping has the advantage of also matching the shape of the gain medium to the output beam shape of a typical laser diode bar. Slab laser amplifiers have been used successfully to produce ultrafast pulses at high average powers, The lasers are used in a master oscillator-power amplifier (MOPA) configuration, with an ultrafast seed pulse. A particularly effective geometry is the "Innoslab" laser, which has been used to demonstrate average powers up to 1.1 kW while producing 55 μJ pulses with 600 fs duration, and 300 W while producing 3 mJ pulses with 900 fs duration [17]. In this case, no CPA was used to temporally spread the pulse. The MOPA configuration with no regenerative amplifier cavity allows flexible repetition rate operation. This allows matching the seeding needs of, for example, XFEL [18], which operates at a pulse rate of 4.5 MHz, but only for 600 μs bursts at 10 Hz.

4.2 Thin disk lasers

Disk lasers and amplifiers rely on removal of heat from the faces of a thin gain medium while propagating the light along the thin direction. The ease of conduction along the laser axis then greatly reduces the radial thermal temperature distribution. Two obvious drawbacks of the thin disk geometry are that

1. The propagation length available for absorption of the pump is very small
2. The gain per pass of the gain medium is small.

Several solutions to these problems are feasible. The most widespread solution is to attach the thin disk to a mirror which also acts as a heat sink, allowing recycling of the pump beam to increase absorption. More detail of this technique will be given later. A conceptually simpler use of thin gain media for high average and peak power operation is exploited by the DiPOLE laser, presently being developed at the Rutherford Appleton laboratories. In the DiPOLE design [19], the gain medium, in this case Yb^{3+}:YAG ceramic, is formed into thin slabs, which are cooled on their faces using a transparent gas – in this case, helium, which has very little optical nonlinearity. Each gain stage is built up of up to 10 of these slabs, with gas coolant flowing between them. The slabs can vary in ion concentration, allowing tailoring of the longitudinal gain profile to suit the amplification process. Initial systems have demonstrated [20] the ability to produce nanosecond pulses of 6.4 J at a repetition rate of 10 Hz, with an optical to optical efficiency of 16%.

A much more common approach to disk lasers is the "active mirror" geometry [21]. In this geometry, a thin gain medium is attached to a mirror which acts as heatsink. The thermal gradients are then small and axial rather than radial, and do not contribute to thermal lensing. Drawbacks of this geometry are that gain per pass is small, and that pump absorption is small. The low gain per pass of the thin gain medium

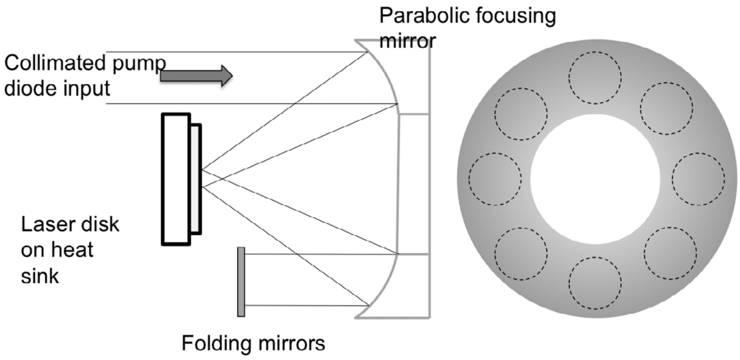

Fig. 1. Multiple pass pumping scheme for disk lasers. Each reflection from the multiple folding mirrors bring the pump beam back onto the parabolic focusing mirror in a different place, so that the total number of pump passes possible is determined by the number of positions on the parabolic mirror (after [22]).

requires that a low-loss cavity be used, as many round trips are necessary. The low pump absorption can be addressed by recycling the pump beam in a multipass geometry. An elegant geometry for this purpose is to use a parabolic focusing mirror with a central hole (illustrated in Fig. 1). In this geometry, the pump is focused onto the sample off-axis using a parabolic mirror. The unabsorbed pump is reflected off the disk back onto a different position on the parabolic mirror, where it is collimated and sent to folding mirrors. The folding mirrors are used to shift the beam laterally, and bring it back onto the parabolic mirror in a different position, from where it is focused back onto the disk. This process can be repeated many times, filling the parabolic mirror, with the limit on the number of pump beam passes given by the number of possible positions on the parabolic mirror. In general high pump beam quality is no so important for disk laser pumping as it is for fibre laser pumping, as the focal spots can be much larger, allowing the use of cheaper pump diodes. However, in the geometry illustrated in 1, the requirement to have multiple reflections filling the parabolic mirror does produce a requirement for good pump beam quality, as a pump with high beam quality will produce a smaller spot on the mirror for a given focus. Optical-optical efficiency is often limited by pump beam absorption.

In CW operation, commercial lasers at the 10 kW level are available if multimode operation is acceptable, and up to 4 kW in single mode operation has been demonstrated [23]. Multiple gain disks can be used within a single cavity to increase available CW output power above the 10 kW level [REF].

Many different laser materials have been demonstrated in the disk geometry, but for high average power operation many applications use Yb^{3+}:YAG. Yb^{3+} is attractive because of its low quantum defect, and disk lasers have been demonstrated using Yb^{3+} in vanadate ($LuVO_4$, YVO_4), tungstate (KGW, KYW), and oxide (Sc_2O_3, Lu_2O_3) hosts, among others [22].

4.3 Ultrafast thin disk lasers

In ultrafast operation, the advantages of thin disk gain media are even more apparent, as the principal issue, nonlinear propagation, can be avoided by increasing the beam diameter, maintaining single mode operation without the thermal penalties associated with use of bulk gain media. Ultrafast mode locked oscillators based on thin disk Yb^{3+}:YAG gain media have been demonstrated [24] up to an average power of 242 W, pulse energy of 80 μJ, and a 3 MHz repetition rate. Modelocking is produced using a semiconductor saturabel absorber mirror (SESAM). The optical cavity, which is almost 24 m long, is folded and kept in vacuum to avoid the optical nonlinearity of the air within the cavity.

Higher pulse energies are available by using thin disk gain media as amplifiers. The tradeoff between high average and high peak power has produced designs optimised for slightly different pulse parameters, but several examples exist of pulse energies above the millijoule level and average powers in the 10 W – 1 kW regime. All three examples discussed here use Yb^{3+}:YAG disks, resulting in relatively long pulses, in the picosecond regime. Very high energy pulses, 165 mJ, at a repetition rate of 100 Hz and a pulse length of less than 2 ps have been demonstrated by Tummler et al. [25]. A multipass amplifier configuration was used, with thin disk laser pumps, with an optical-optical efficiency of 14%. The beam quality was high, with M^2=1.1. At higher average powers and lower pulse energies, 3 mJ pulses at 10 kHz have been demonstrated [26,27], with a pulse length of 1.6 ps, from a laser designed principally for pumping of optical parametric chirped pulse amplifier (OPCPA) systems. These pumps allow the OPCPA to produce very high energy single-cycle pulses for attosecond pulse generation. The configuration is a regenerative amplifier, pumped by CW laser diodes, with an optical-optical efficiency of 26%. The highest average power for a femtosecond pulse disk system [28] is 1.1 kW, and pulse energy of 1.38 mJ. Pumping is again via laser diodes, with an optical-optical efficiency of 44%. This system produces longer pulses, at about 7 ps, from a multipass configuration. Several publications put forward the possibility of Joule-class lasers using thin disks.

5 Ultrafast fibre lasers

Fibre lasers deal with the two issues of nonlinearity and thermal distortion in a completely different way to thin disk lasers. The geometry of a fibre laser increases the surface area of the gain medium in a more extreme way than the thin disk laser – the gain medium is effectively one-dimensional rather than two-dimensional. Thus the effectiveness of thermal transport out of the gain region is very high. The waveguide geometry aids minimisation of the effects of small thermal distortions, as the distortions have to be large on the scale of the waveguide index profile to significantly alter the mode propagating within the fibre. Nonlinear propagation issues are, however, significantly worse for fibre lasers, because of the difficulty of reducing the peak intensity by making the beam larger, and the increase in interaction length.

One very significant development in the history of high average power fibre lasers is the development of *cladding pumping*, allowing for the use of relatively low-quality laser diode beams to end-pump a fibre. Cladding pumping uses a fibre with two cores, one within the other. The outer large core guides the pump light. The inner, smaller core is doped with the active ions, and laser amplification occurs within this smaller core. The outer core can be multimode, and the inner core is designed to be single mode. The small active core area increases the absorption length, but the low loss of the fibre means that the increase in length is acceptable. This idea of "cladding pumping", first demonstrated [29] by Snitzer et al. in 1988, underlies all of the high average power fibre laser work described in this review, and influences the design of fibres for high average power ultrafast fibre lasers.

In CW form, the average powers available from Yb-doped silica fibre lasers are already very high – single fibres demonstrated CW power output above 1 kW in 2004 [30], and above 10 kW by 2010 [31]. Beam-combined CW fibre lasers with powers of 50 kW are available commercially.

The major issue for ultrafast fibre lasers is that of nonlinearity, because of the small mode areas used compared to other systems. Ideally, a value of B less than 1 would be used in all circumstances, but this limits the peak intensity for a given beam size, fibre length and stretch factor, and so higher values of B are sometimes used.

5.1 The Yb fibre laser

The first demonstration of CPA in cladding pumped high power fibres was in 1995, using fibres co-doped with Er and Yb. The ytterbium was used to absorb the pump light and transfer excitation to the Er ions, which produced the laser amplification at 1500 nm. This system anticipated many of the features of later ultrafast fibre laser designs, using an oscillator whose pulse output was stretched using a chirped fibre Bragg grating to provide pulses of length ∼1 ns. The stretched pulses were coupled into a series of fibre amplifiers: an Er-doped fibre preamplifier and an Er/Yb doped power amplifier. The output from the power amplifier was compressed using the same chirped fibre Bragg grating. An average power level of 600 mW of compressed output was achieved, with pulses of 310 fs at a repetition rate of 18 MHz, giving pulse energies of ∼30 nJ. Millijoule-level femtosecond pulses were first demonstrated in 2001, using CPA and a 50 μm core amplifier fibre [32] to produce pulses with energy of 1.2 mJ and pulse length of 380 fs.

Thermal considerations have led to the use of Yb-doped fibres almost exclusively as average power of ultrafast fibre lasers have increased above the Watt level. Yb-doped fibre CPA was first demonstrated [33] in 2000, again using a two-stage cladding pumped amplifier chain producing 5.5 W of 140 μJ pulses with ∼160 fs duration. Since the development of Yb-fiber CPA, average powers and pulse energies have increased significantly. Cladding-pumped designs with much larger core areas have allowed increase in pulse intensities and energies, reducing the effect of nonlinearity by reducing peak intensity for a given stretched pulse duration, typically a few ns. However, increasing core area also has several detrimental consequences for mode structure and for average power handling.

For a simple step index fibre, the condition of single mode operation is that the fibre's normalised frequency, or V-number, given by $\frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$, where a is the core radius and n_1 and n_2 are the index of core and cladding respectively, should be less than 2.4. As the fibre core radius a is increased, the factor $\sqrt{n_1^2 - n_2^2}$, known as the numerical aperture of the fibre (NA), must become very small to maintain single mode operation. The propagation loss due to bends in the fibre increases as $(NA)^{-3}$, so that a large core fibre must be kept completely straight over its whole length, leading to the oxymoronic title of "rod fibre". The use of photonic crystal fibre structures (PCF) can relax the single mode criterion, and even produce fibres that are single mode for all wavelengths in some geometries [34]. However, mode area is difficult to increase indefinitely while retaining single mode operation.

It is possible to amplify a single mode within a multimode fibre structure, particularly if the fibre is held perfectly straight. This allows the use of very large cores. The CW 1.38 kW power quoted in [30] used a core diameter of 40 μm, and a V-number of 5.7, allowing a few modes to be supported. However, for ultrafast pulsed fibre lasers, the use of very large cores (and associated large mode field diameters, or MFD) at high average powers results in the onset of rapid fluctuations of the output spatial mode above a particular threshold power. These rapid fluctuations, known as transverse mode instabilities (TMI) are typically observed for average power levels above ∼100 W. These instabilities manifest themselves as rapid changes in the output mode of the laser, as power is coupled from the lowest order mode to high order modes. They are thought to arise from a combination of thermal and optical effects inducing mode coupling from fundamental to higher order modes [35,36]. They provide an upper limit to the average power available from a fibre of a particular mode area. A summary of average powers at which TMI is observed in different fibre designs and mode field diameters has been made by Zervas et al. [37]. The upper limit on the amplifier B integral necessitates the use of large mode areas, and thus implies low TMI thresholds for pulse energies $> 100\,\mu$J.

At present, the highest single pulse energy [38] produced in a single fibre is 2.2 mJ, produced at an average power of 11 W from a fibre with very large mode diameter – 105 μm. The pulse length is 480 fs, and the final amplifier B-integral was 6 rad, indicating some nonlinear phase shift within the final amplifier. In order to increase the average power, the mode area of the fibre must be reduced to prevent the onset of mode instabilities, but this has the effect of limiting the pulse energy. Stutzki et al. have demonstrated an average power of ∼300 W from an ultrafast amplifier system producing 75 μm pulses with duration of 640 fs. Changes in the PCF design were made to increase the threshold for TMI, allowing the use of a mode diameter of 62 μm. The highest average power from a femtosecond pulsed system [39] is 830 W, produced using a non-PCF core fibre with a relatively small mode diameter of 27 μm. The pulse energy produced was 11 μJ, with a duration of 640 fs. The final amplifier B-integral was 11 rad, with the smaller core increasing the nonlinear phase shift and lengthening the pulse.

5.2 Divided pulse amplification

Within the fibre laser area, several new techniques are being applied to try to increase the output of a single fibre femtosecond amplifier. Nanosecond pulse fibre amplifiers have been demonstrated [40] with pulse energies of 26 mJ, much higher than the 2.2 mJ demonstrated for a femtosecond system, indicating that with suitable input pulses more energy can be extracted per fibre. The high-energy pulses produced were ∼60 ns long, indicating that the focus must be the degree to which a pulse can be stretched before amplification. Longer pulses not only provide better energy extraction, but also decreased nonlinearity within the amplifier – the fixed limit on peak power imposed by nonlinearity means that extra pulse stretching before amplification translates directly to increased peak power after compression.

In general, stretched pulse length in CPA is limited by compressor design. One approach to get round this limitation is provided by divided pulse amplification (DPA), first demonstrated by Zhou et al. in 2007. In DPA, instead of spreading the pulse using dispersion, multiple replicas of the pulse in time are created using beamsplitters. The peak power is thus reduced by a factor equal to the number of replicas. The replicas are recombined after amplification using the same (or a similar) beamsplitter chain, to produce a final pulse with higher peak power.

DPA can be used in combination with CPA, so that a sequence of replicated stretched pulse is amplified and recombined, with recombination using both a beamsplitter array and a grating-based compressor. One major drawback of the DPA approach [41] is that the initial pulse of a train sees much higher gain than the other pulses, so that after amplifications the pulse train has very uneven intensities. This effect can be minimised by variation of the amplitude distribution of the input pulses, whose energies start off small and increase through the train, so that after amplification with a partially-saturated amplifier the amplified energies are equal. This represents extra complication, but has been demonstrated successfully using active control [42], producing pulses of energy of 2.4 mJ after amplification, and 1.25 mJ after compression, from a fibre with mode field diameter of 75 μm. The reduction of efficiency of compression observed in this work from its typical vale of 75% to ∼50%

is attributed to increased nonlinear phase shifts due to amplitude fluctuations and phase distortions within the DPA system. Up to 6.5 mJ pulse energy was available from the fibre, but stable recombination was only possible up to 2.4 mJ output. The average power produced was 37 W. The potential for higher energy pulse output from single fibres using DPA will depend on the reduction of fluctuations and improvement of recombination efficiency at high pulse energies.

5.3 Pulse stacking

The ability of optical fibre amplifiers to handle high average powers with small pulse energies leads to the idea that coherent pulse addition within a passive optical cavity could be used to produce high energy, low repetition rate pulses from low energy high repetition rate pulse trains. Pulses launched into an enhancement cavity with high Q-factor, whose round trip time is the same as the pulse repetition rate, results in pulse buildup within the cavity. Enhancement cavities have been demonstrated to be effective in production of high energy pulses for experiments such as high harmonic generation [43], but practically their use is limited by the requirement for the experiment to be performed within the cavity, while not reducing the cavity Q-factor. An alternative is to use the equivalent of cavity dumping in laser cavities, and switch the pulse out of the cavity using an optical element once the pulse has built up.

Cavities have been demonstrated [44] using Yb:fibre laser pumping with intracavity powers up to 400 kW, and an enhancement factor of ∼1270, using 250 fs pulses, corresponding to a pulse energy of 1.6 mJ at 250 MHz. While this is a significant advance on the performance of fibre lasers alone, the pulses were not switched out of the cavity for use in experiments.

Switching pulses out of a high-Q enhancement cavity presents a formidable technical problem, because of the high repetition rates and short times involved, and the requirement for a very low-loss switching element. High-speed choppers have been proposed as a possible solution, using a small mirror mounted on the synchronised chopper to reflect the pulse out of the cavity. No extra cavity loss would be introduced, but the rotation speeds necessary are hard to achieve, and such a setup has not yet been demonstrated [45].

5.4 Beam combination

It is clear that solutions to the issue of transverse mode instability are necessary to further increase the pulse energy and average power of a single fibre amplifier, because of the trade-off between nonlinear phase shift during the pulse and amplifier mode area. However, a different solution to the problem of increasing pulse energy lies in the ability to effectively combine the outputs of multiple lasers, producing a modular laser whose pulse energy is determined by the number of lasers being combined rather than the physical properties of the lasers themselves. Beam combination can be performed in principle with any kind of laser; the actual price and performance of a beam-combined laser system will depend on engineering issues like the efficiency of combination, the ability to mass-produce laser modules, and the long-term stability of each module.

Fibre lasers offer themselves to beam combination in a more convenient form than disk lasers, principally because of the relative simplicity of the fibre system. The high power disk lasers producing described in Sect. 4.3 are complex optomechanical devices, typically needing pump laser optics allowing tens of passes of the disk, and regenerative amplifier cavites. Conversely, optical fibre amplifier systems are relatively simple optomechanical devices, using fibre coupling between components whenever possible. Thus the idea of mass production and stable operation of multiple combined fibre systems is sensible, particularly given the wealth of experience of manufacturing in the rapidly-growing commercial fibre laser industry.

Beam combination of CW lasers is a commercially-available technology. Coherent beam combination must be used, however, in any system where the coherence properties of the laser are important. For CW lasers, this means matching the phase of multiple sources, requiring accurate phase measurement. Many techniques for controlling the relative phase of multiple beams have been developed including the Hänsch-Couillaud [46] and LOCSET [47] techniques. In the case of fibre amplifiers, the largest number of multiple channels whose combination has been demonstrated is 64 fibre amplifiers, using a tiled aperture geometry, and using quadriwave lateral shearing interferometry (QWLSI) for phase error determination [48].

For ultrafast lasers, beam combination is complicated by the requirement to match not only the phase but also all higher orders of dispersion produced with the amplifiers. In most schemes developed so far, phase and group velocities are matched – i.e. the pulse envelopes are synchronised as well as the carrier waves, but higher order dispersion is not actively controlled. A number of schemes have been developed, but the most successful demonstration so far has been coherent combination of high energy pulses from 4 fibre amplifiers [49]. This system comprises four amplifiers, each producing around 130 W average power at a repetition rate of 400 kHz. Beam combination is via a tiled aperture technique, where the beams are combined using polarising beam splitters, and their relative phase controlled via Hänsch-Couillaud detectors. This system shows a combined average power of 530 W, producing pulses of energy 1.3 mJ and length 670 fs. The combination efficiency is ~93%. The prospect for combination of many more beams is good – theoretical work has shown that the decrease in combination efficiency due to phase and amplitude fluctuations converges to a fixed value as the number of channels increases, rather than continually decreasing [50]. Practical demonstrations of interferometric phase measurement and control of multiple beams in the manner of reference [48] have been performed at kHz bandwidths [51], and theoretical predictions of measurements of up to 10,000 individual sources using a single camera exposure at high bandwidth have been made using current capability in camera and computer technology [52].

5.5 Pulse length

The typical pulse length for a high average power fibre amplifier in most of the examples given so far is between 300 and 600 fs. The bandwidth of Yb^{3+} in glass is sufficient to support much shorter pulses, but the gain narrowing inherent in the amplification process reduces the available bandwidth. Because the gain spectrum of Yb^{3+} is broad in glass, high average power amplifiers can be produced with different central wavelengths, and so through coherent combination of pulses with different spectra, a single pulse with shorter duration can be created. Spectral beam combination was originally demonstrated with CW lasers as a way of increasing the CW output power of a source [53], and is now in common usage. Typically, a diffraction grating is used to combine multiple beams at different incident angles and the same diffraction angle. In a femtosecond system, it is necessary to make sure that there is no spatial chirp on the output beam, and so filters are used that are not spectrally dispersive. Proof of this principle was demonstrated using a three channel system, in which the incoming spectrally broad (12 nm) pulse was sliced into three spectral segments using dichroic filters. Each was amplified in a separate amplifier fibre, via a delay line. The final pulse was reassembled coherently using LOCSET. The individual channels after amplification had pulse lengths of around 1400 fs, and the final pulse after beam combination had a pulse length of 403 fs, close to the transform limit. Combination efficiency was 76.3%. Real pulse shortening has been demonstrated at average powers of 10 W. In this experiment, two channels of fibre CPA are combined whose individual pulse lengths were already around the shortest observed in a high average power amplifier, with autocorrelations in each channel of around 400 fs. Coherent combination was controlled using frequency tagging. The combined pulse has a bandwidth of 19 nm and a duration of 130 fs, close to the transform limited bandwidth of 115 fs, and much shorter than any previously demonstrated single fibre Yb^{3+} amplifier.

5.6 Pulse contrast

Contrast in high peak power femtosecond systems is absolutely critical, because any form of pre- or post pulse will have high enough intensity to seriously affect the experiment. Contrast in fibre CPA systems has been shown to be very sensitive to small ripples in the input to the CPA system, because fibre CPA systems generally have to tolerate a higher degree of nonlinearity than other amplifiers, and are operated at higher values of the B-integral. Hence any self phase modulation within the amplifier can enhance ripples in either amplitude [54] or phase [55,56]. In order to clean up any pre and post pulses which are present, the technique of cross-polarised wave generation (XPW) [57] can be used. XPW generation uses a third-order nonlinear process to create a wave polarised orthogonally to the original, whose intensity is proportional to the cube of the input intensity. This cross-polarised wave can be selected using linear polarisers, largely removing any pedestal or pre/post pulses from the beam. At 1 μm, contrast increases of 10^3 have been observed, along with pulse duration reduction by a factor of $\sqrt{3}$. XPW has been demonstrated in a fibre CPA system [58]. In this case, pulses of 200 μJ energy and 400 fs duration were used to produce high-contrast output pulses of 37 μJ and significant temporal compression down to 115 fs. The effectiveness of the cleanup and compression are evident, but the efficiency of the process is not high – in this case, about 20%. The maximum theoretical efficiency is only 52%. Thus XPW, although effective at increasing contrast, will always cause significant loss, and more conventional techniques such as plasma mirrors [59] may be more effective at very high pulse energies.

6 Future prospects

A summary of the peak and average powers available for a selection of sources described in this review is given in Fig. 2. Average power is plotted on the x-axis, and peak on the y-axis. Lasers closer to the top right corner of the diagram are more attractive for high peak and average power applications. As well as the various sources described in the text, a commercial Ti:sapphire laser with average specifications is included. It is interesting to note from this plot that disk lasers in general have produced higher peak and average powers than single fibre lasers. The beam-combined fibre laser in reference [49] has specifications similar to the disk lasers shown.

The prospects for future sources are also interesting to speculate upon. The key issue here is scalability – average power scaling of a factor of 10, and peak power scaling by a factor of 10,000 are necessary to reach the levels required for some applications. The scaling of fibre amplifier systems by beam combination is already beginning, and powers are improving considerably. The ability to scale disk-based systems is hampered by their complexity and cost; disk-based systems tend to require significantly

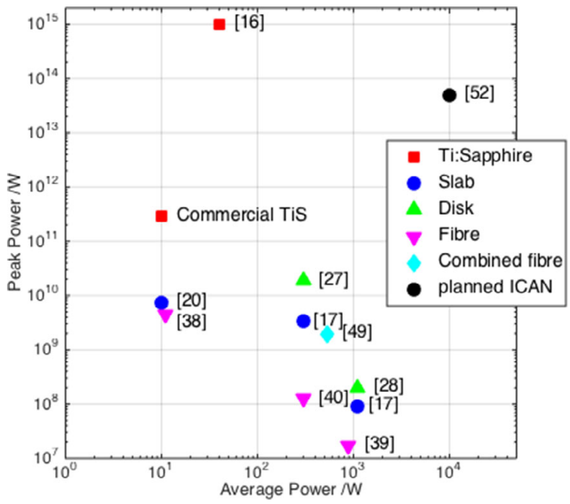

Fig. 2. Peak power vs. average power for a number of sources described in this review. Reference for each source is given in brackets next to each point.

more optomechanical components than an all-fibre amplifier system, increasing cost and decreasing stability. In addition, the pulses available from disk lasers are significantly longer than those available from fibres – typically 1 – 2 ps rather than 500 – 600 fs, making the additional need to further compress the pulse even more important.

The behaviour of light sources composed of the beam-combined output from ∼1000 individual lasers has a number of intriguing possibilities. The noise properties of such beams will be very different from traditional lasers; the ability to control individual phases means that in principle beams can be corrected for aberration of optics, etc. Even prepulse behaviour will be subject to statistical reduction. All of these properties make CAN lasers more controllable than regular sources, a fact which can be exploited in their design.

Overall, the goal of multi-kHz, Joule class ultrafast lasers requires a sizeable amount of research, but is being approached from several different directions. These lasers will open up whole classes of applications which were previously limited in their practicality by repetition rate.

The author would like to acknowledge funding via the ICAN project under FP7.

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