Latest development of high power fiber lasers in SPI

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Summary

High Power Fiber Lasers (HPFLs) and High Power Fiber Amplifiers (HPFAs) promise a number of benefits in terms of their high optical efficiency, degree of integration, beam quality, reliability, spatial compactness and thermal management. These benefits are driving the rapid adoption of HPFLs in an increasingly wide range of applications and power levels ranging from a few Watts, in for example analytical applications, to high-power >1kW materials processing (machining and welding) applications.

This paper describes SPI's innovative technologies, HPFL products and their performance capabilities. The paper highlights key aspects of the design basis and provides an overview of the applications space in both the industrial and aerospace domains.

Single-fiber CW lasers delivering 1kW output power at 1080nm have been demonstrated and are being commercialised for aerospace and industrial applications with wall-plug efficiencies in the range 20 to 25%, and with beam parameter products in the range 0.5 to 100 mm.mrad (corresponding to M^2 = 1.5 to 300) tailored to application requirements.

At power levels in the 1 – 200 W range, SPI's proprietary cladding-pumping technology, GTWave™, has been employed to produce completely fiber-integrated systems using single-emitter broad-stripe multimode pump diodes. This modular construction enables an agile and flexible approach to the configuration of a range of fiber laser / amplifier systems for operation in the 1080nm and 1550nm wavelength ranges.

Reliability modelling is applied to determine Systems margins such that performance specifications are robustly met throughout the designed product lifetime. An extensive Qualification and Reliability-proving programme is underway to qualify the technology building blocks that are utilised for the fiber laser cavity, pump modules, pump-driver systems and thermo-mechanical management.

In addition to the CW products, pulsed fiber lasers with pulse energies exceeding 1mJ with peak pulse powers of up to 50kW have been developed and are being commercialised. In all cases reducing the total "cost of ownership" for customers and end users is our primary objective.

1. Introduction

Demand for compact, highly-efficient CW lasers delivering stable output powers in the 1W to 1kW+ range in a well-confined beam has been confirmed. Fiber lasers based on active-ion-doped cladding pumped optical fibers offer an elegant and cost-effective solution to meeting these application needs. Whilst laser users may typically be agnostic to the technology employed within the laser system, the recognised advantages of fiber lasers are stimulating their rapid uptake in both new and established application fields.

In certain regards, the industry may already be approaching the upper limits of what can be achieved with conventional diode-pumped solid-state (DPSS) laser systems using disks or rods as the lasing medium, particularly in terms of the inter-relationships between key performance parameters such as maximum power rating, beam quality, overall efficiency, directly-cooled operation and space requirements. Factors constraining the performance and scalability of

DPSS technology include the physical and geometrical configuration of the laser cavity, stability of long resonators, and specifically the need to inject the pump energy into the active medium and to extract waste heat from the same confined space; complex cavity arrangements are frequently employed accordingly.

In contrast, the fiber laser comprises an elongate laser cavity in which pump energy is absorbed and waste heat generated and dissipated over metres of fiber; thermal stabilisation of the laser cavity is therefore straightforward. Moreover, the transverse beam characteristics of the fiber laser are determined by the fiber waveguide structure itself. In addition, overall wall-plug efficiencies of 24% are achievable in Yb-based fiber lasers, an improvement of typically 50% over alternative diode-pumped technologies.

These intrinsic features of High Power Fibre Lasers therefore offer a number of attractions and advantages to the end-user, potentially overcoming constraints of conventional laser systems.

This paper presents a technical overview of SPI's recent developments in high-power fiber lasers, demonstrating the status of technology, laser design, product development and performance, targeted applications.

2. SPI Fiber Laser Technologies

2.1 Cladding-Pumped fibers for end-pumping high-power fiber lasers

Rare-earth doped silica fiber has been proven as an excellent solution for all-optical amplification and has been extensively and reliably deployed in the telecom arena for many years. Silica fibers are also attractive for high power amplifiers and lasers because silica glasses have a high damage threshold, the surface-to-volume ratio of an optical fiber is high so heat dissipation is straightforward, the gain medium is incorporated in a waveguide so it is possible to maintain diffraction-limited output, and fiber manufacturing technology makes it straightforward to fabricate fibers and fiber laser cavities in long lengths tailored to provide the beam quality for any particular application.

Recently there have been significant developments in the area of cladding pumped double-clad doped-fibers for very high power fiber lasers and amplifiers: In this approach the fiber core is heavily doped with the active lasing ion (e.g. Yb, Er, Nd, Tm) and the clad-silica fiber is coated with a low refractive index material; pump light is launched into the cladding of the optical fiber (typically in the range 125 um to 600um diameter), see Figure 1.

The silica inner cladding and the low index coating material make a high numerical-aperture multi-moded waveguide for the pump allowing high-power multi-mode semiconductor diode lasers to be used. This offers advantages both in terms of cost-per-Watt, and in terms of the availability of much higher-powered pump lasers (several tens of Watts for high-brightness single-emitter devices and in excess of 1kW for stacked diode bars).

In operation, the pump light propagates along the glass cladding of the optical fiber and is absorbed by the active ions in the core. This double-clad fibre configuration is typically used for end-pumped fiber lasers; note that special measures are often taken to ensure that the pump light is absorbed efficiently over a reasonable device length, particularly to prevent the pump light propagating in helical modes in the cylindrically-symmetric double-clad fibers, thereby reducing the pump absorption.

It should also be noted that with dual-end pumped lasers there is a requirement to interrupt the signal fiber in order to launch the pump light; usually dichroic beam coupling components are used to launch and separate the pump and signal and result in an increase in cavity insertion loss.

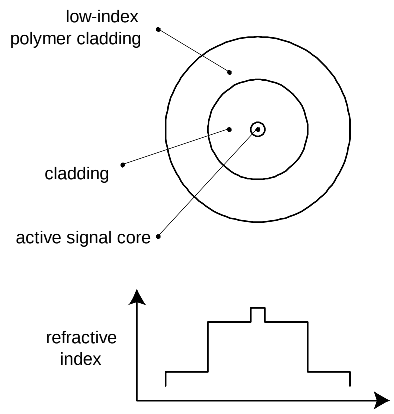

Figure 1. Cross-section and refractive index profile of a standard double-clad fiber

2.2 GTWave™ cladding-pumped fiber

SPI's GTWave™ fiber has been developed as a simple and novel approach to address the problems with standard cladding-pumped double-clad fibers. The proprietary fiber design of GTWave™ allows a fully integrated fiber laser cavity in which high-power multi-mode pump diodes are coupled into the active fiber without needing additional complex optical components and without interrupting the signal path at all.

GTWave™ fiber is a structure that comprises one active signal fiber and one or more multi-mode pump fibers that are made to contact each other and are surrounded by a common coating of a low refractive index polymer. Figure 2 illustrates the cross-sectional appearance and refractive index profile of GTWave™. The concept of GTWave™ is to provide physically-separate fibers for pump and signal that can be 'broken-out' from the common coating material and independently spliced to multi-mode pigtailed high-power pump diodes and standard single-mode transmission fibers respectively.

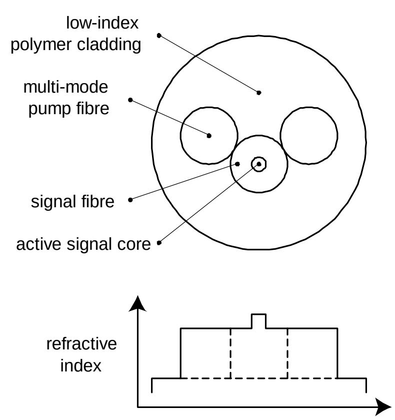

Figure 2. Cross-section and refractive index profile of GTWave™

Figure 3 illustrates how the three fibers of standard GTWave™ are broken-out from the coating in a "trifurcating splice" that joins them to standard multi-mode and single mode transmission fibers at either end.Pump light launched into the multi-mode fibers cross-couples between all of the fibers in the structure (see Figure 3) and is absorbed by the active ions in the core of the signal fiber. A noteworthy feature is that the asymmetric structure of the GTWave™ fibre enhances the pump absorption by the signal core.

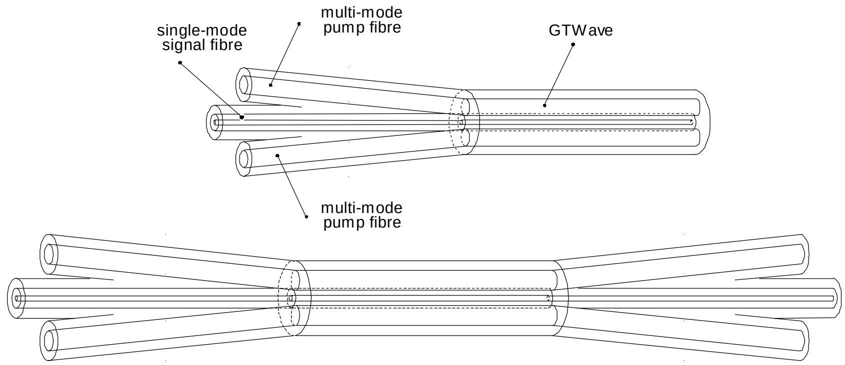

Figure 3. (*Top*) GTWave™ fiber is 'broken-out' into two multi-mode pump fibers and a single-mode signal fiber for ease of launching pump and signal light

(*Bottom*) illustration of GTWave™ with standard pigtails at either end

One of the key advantages of GTWave™ is that there are inherently more 'ends' of fiber that can be pumped: in the case of standard GTWave™, there are four possible pump ports that can be used without interrupting the signal fiber. SPI's advanced fiber design and manufacturing methods allow a higher level of pump absorption than is possible with standard core-doping designs, whilst maintaining single-mode signal characteristics. Moreover, compared to other side-pumped configurations, the GTWave™ structure is inherently more reliable because it does not require any intervention along the fiber length to introduce the pump light.

2.3 GTWave™ power scaling: By concatenating multiple GTWave™ sections it is possible to extend the cavity length, to increase the number of pump injection points, and to increase the output power accordingly.

Figure 4 illustrates the performance of a single GTWave™ spool delivering in excess of 70W.

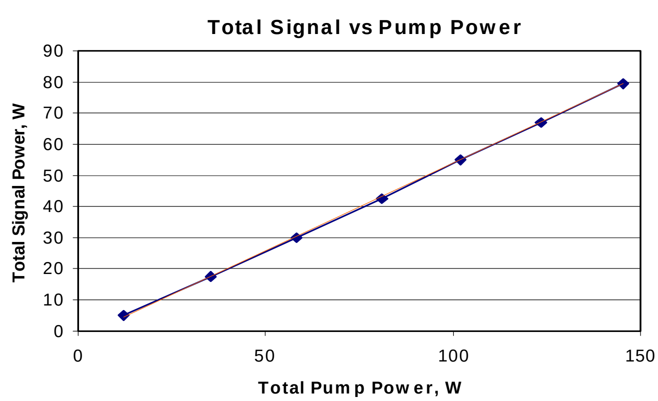

Figure 4: Single GTWave spool performance when pumped at 915nm

Concatenating two or more GTWave™ spools enables CW power levels in excess of 100W to be achieved. Figure 5 shows the beam quality parameter for such a device operating at 1085nm. Multiple GTWave™ lasers can be combined either incoherently or coherently for kW power systems and beam-steering applications respectively.

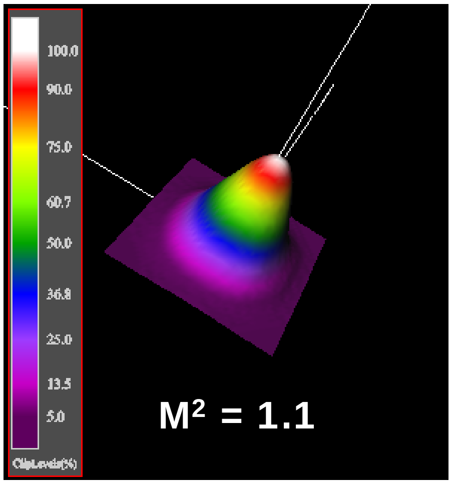

Figure 5: Beam Quality parameter for 100W GTWave concatenated spool lasing at 1085nm

Figure 6: GTWave Laser Cavity Module containing active fiber, Fiber Bragg Grating reflectors and air-cooling heat exchanger

This technology has been incorporated into product platforms for operation either in air-cooled configuration or in water-cooled configuration (dictated primarily by customer application needs and customer preference). Figure 6 shows an example of a fully integrated 50W air-cooled GTWave™ sub-assembly ready for incorporation into a laser product.

3. High-Power laser pump modules

SPI utilizes commercially sourced broad-stripe multi-mode laser diode emitters for pumping its range of products based on GTWave™ active fiber technology. The outputs from a number of pump diodes are combined using fused-fiber beam combiners and are thereby coupled (via a straightforward fusion splice) into the GTWave™ pump fibers.

As with the GTWave™ modules, pump modules using air-cooling or water cooling are utilized according to overall power level, application requirements and customer preference. Figure 7 below illustrates an air-cooled pump module providing ~70W of combined pump power at 915nm; compact pumping modules with up to 140W output are utilised.

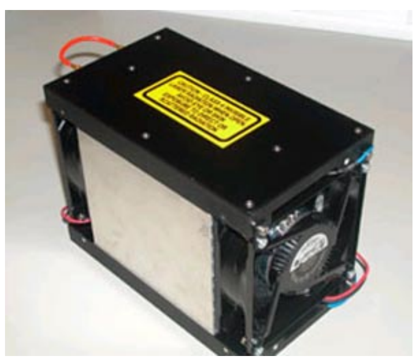

Figure 7: 70W Air-Cooled Pump Module

The pump module driver board and internal connections are designed to enable direct modulation of the diode drive current at fast rise- and fall-times in order to ramp the fiber laser output power where the laser application so requires. Thermal design of the pump block is an important element to ensure that the maximum operating temperature of the diodes is contained within SPI's design limits for full load and overload operation at the laser system's specified upper environmental operating temperature limit.

All passive and active components in the pump module have been individually qualified for reliability, and the pump modules themselves are undergoing extensive long-term load testing to prove subsystem reliability.

4. SPI redPOWER™ fiber lasers

The all-fiber structure of SPI's GTWave™ and pump module building blocks facilitates the design of a range of fiber lasers and amplifiers with characteristics optimised for a variety of specific applications, operating wavelengths, cooling configurations, and output power control formats.

Design for reliability is a key aspect of the product design and specification. Using statistical data for the various components and sub-systems operating in the intended application environments (typically temperature driven), and projecting forward for the defined lifetime of the laser, suitable Start of Life and End of Life operating points are calculated to determine the necessary degree of pump redundancy margin required to assure the targeted reliability.
For example, design lifetimes of 10,000hrs, 30,000hrs and higher have been adopted to ensure guaranteed availability dependent on customer operational requirements.

Figure 8: 100W Water-Cooled redPOWER fiber laser (19" rack, 6U high), with beam delivery optics

SPI's Commercial laser system "redPOWER™"offering using GTWave™ building blocks in the 1080nm wavelength window include 20W to 50W air-cooled, 100W water-cooled and 100W air-cooled units. Figure 8 (above) shows an example of the 100W water-cooled product; the system is 19" rack-mountable. Beam delivery systems have been developed to meet a variety of application needs, such as for beam expansion where the output power level of the laser might otherwise induce damage in the materials used for beam management external to the laser.

Each system is equipped with the necessary physical, electronic and software interfaces to enable safe incorporation within a higher-level (application-specific) system.

In addition to the "standard" fiber lasers operating in the 1080nm region, amplifiers and Master Oscillator Power Amplifiers (MOPAs) using GTWave™ technology have been successfully developed and commercialised both in the 1080nm window and also in the 1550nm window. These sub-systems have also formed the "front-end" of multi-stage very high power MOPAs operating at power levels of several hundred Watts (see Section 4 below).

Polarisation maintaining performance has also been achieved and will be commercialised during 2004.

5. Development of Very High-Power Single-Fiber Lasers (VHPSFLs) & Amplifiers

In parallel with the development of GTWave™ technology and related redPOWER™ products, SPI and the University of Southampton's Opto-electronics Research Center (ORC) have been working to extend the technology and performance range of very high-power ***single-fiber*** lasers and amplifiers towards and beyond the 1kW power level. This work has been organically funded in part (for wide application) and has also been funded under DARPA Programme Contract MDA972-02-C-0049. The scope of activities includes not only Yb-doped fiber lasers but also Er-Yb-doped fibre lasers operating in the 1.55um region and Master Oscillator Power Amplifiers (MOPAs) working in both wavelength windows.

Figure 9 shows an example configuration of a "broadband" VHPFL test arrangement using dual-ended pumping.

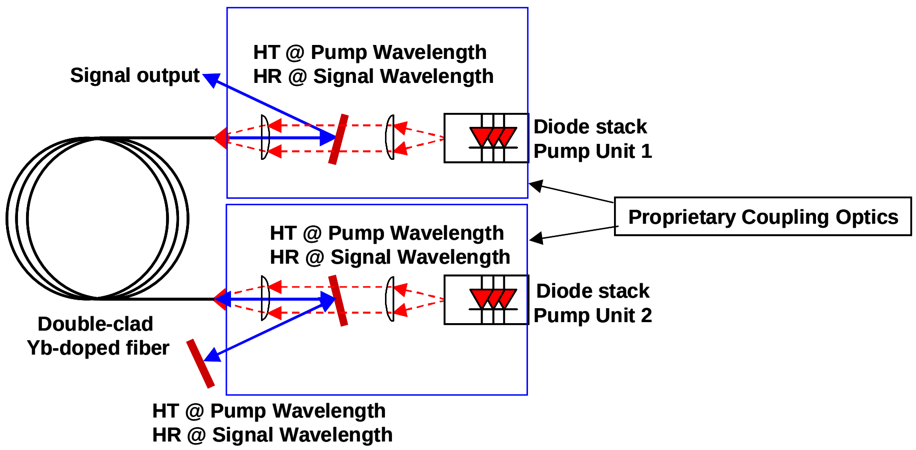

Figure 9: VHPFL: Schematic of dual-ended cladding pumped fiber laser

Although these devices have utilised end-pumped fiber cavities using commercially available high-brightness diode stacks, multiple diode bars or multiple-single emitters could also pump the fiber lasers. Proprietary coupling optics and beam combiners are used to facilitate the efficient coupling of the multiple diode sources into the fiber at optimum brightness.

Fiber designs and compositions have been optimised to facilitate pump injection, pump absorption, optical conversion efficiency, and output signal beam quality, whilst maintaining optical power densities below physical damage thresholds for the silica glass and polymeric cladding materials. For the MOPA developments (targeted principally at aerospace applications) single frequency and polarisation-maintaining performance has also been targeted.

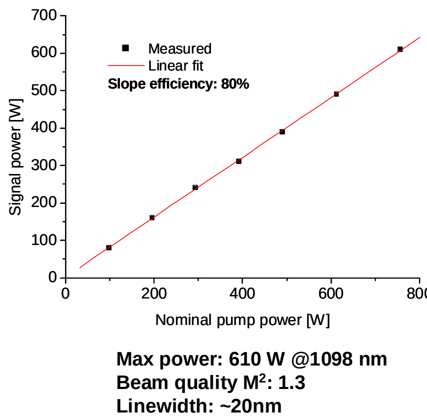

Figure 10: >600W HPFL with M^2 = 1.3: June '03

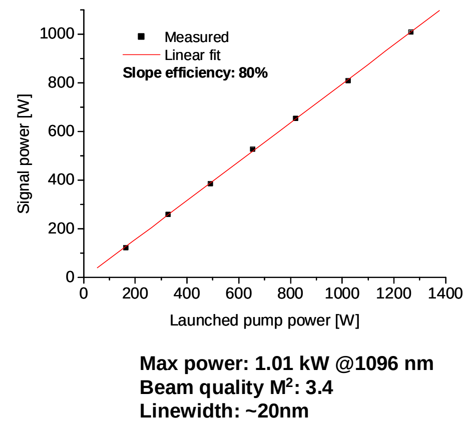

Figure 11: 1kW HPFL with M^2 = 3.4: August '03

Using a specially-designed Yb-doped large mode area (LMA) fiber with a core diameter of approximately 28um, end-pumped at 975um by a 1kW (max) source, a total output power of 610W at ~1.1um was achieved with a noteworthy M^2 value of 1.3, as shown in Figure 10 above. The output signal shows a highly linear response and demonstrates that the laser output was pump-power limited. The result also demonstrates noteworthy features of the high-power fiber laser, namely the very low threshold level and the excellent slope efficiency, thereby providing an overall wall-plug efficiency of ~25%.

In a further development using a total pump power of 1.5kW (max) at 975nm, by using dual-ended pumping of a fiber with larger overall diameter and a low-moded multimode core, an output power of >1kW was achieved, as shown in Figure 11. Note that in this case an M^2 value of 3.4 was achieved, corresponding to a beam parameter product (BPP) in the region of 1mm.mrad.

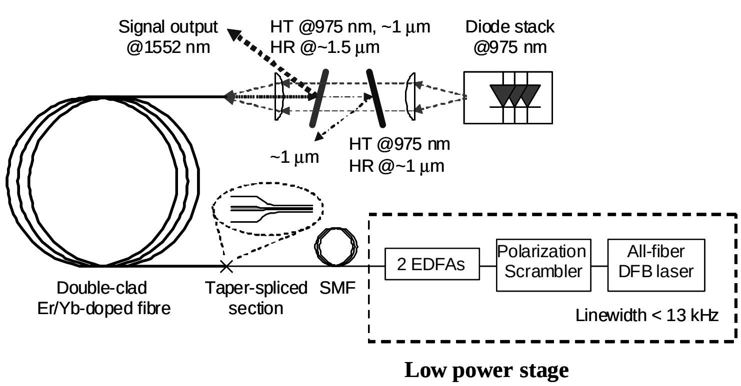

Figure 12: 1552 nm single-frequency MOPA configuration

Significant progress has similarly been made in the development of high-power single-frequency MOPAs both in the 1080nm and 1550nm regions: For example, in a MOPA system as shown in Figure 12, comprising an Er-Yb-doped DFB fiber laser source, GTWave™-based pre-amplification stage and a 975nm end-pumped final-stage amplifier utilizing Er-Yb-doped double-clad fiber, a total output power of 83W was obtained at the eye-safe wavelength of 1552nm with a linewidth of 17 kHz at the final-stage output and an M^2 value of 2.0.

6. Commercialisation and application of Very High-Power Single-Fiber Lasers (VHPSFLs)

Productisation of the aforementioned VHPSFL CW laser technology has already commenced; SPI will be commercially supplying a system within the first half of 2004.

In the VHPFL product definition process, the potential application space for 1kW HPFLs with well-confined beams has been mapped: Figure 13 schematically summarises the findings and future projections for fiber laser systems with CW output powers up to 100kW. SPI's fiber technology addresses all significant markets and applications, with the added advantages of high wall-plug efficiency and fiber beam delivery.

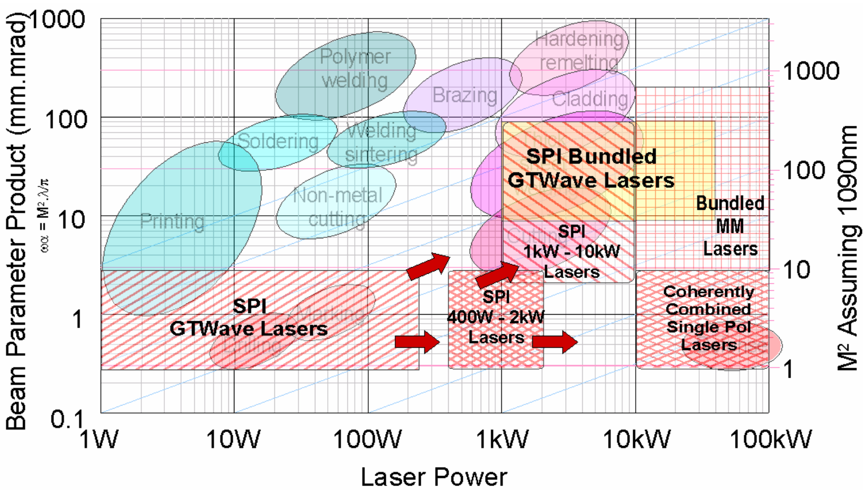

Figure 13: Application Space for Fiber Lasers

7. Conclusions

With the development and on-going qualification of high-power cladding-pumped fiber lasers based on our GTWave™ pump-coupling technology, SPI has brought to market a range of CW and fiber lasers and amplifiers operating in the 1.08um and 1.55um regions. Pulsed fiber lasers with peak powers up to 25kW have been demonstrated and are also being commercialized.

Parallel developments of very high-power end-pumped single-fiber CW lasers and MOPAs have shown the demonstrated that power scaling into the 1kW domain and beyond. First systems in the range 400W to 1kW are being implemented on a commercial basis now.

The advantages and benefits of fiber laser and amplifier technology are gaining increased recognition in a broad range of applications; initial results indicate that their advantageous properties will stimulate continued growth both in terms of power scaling and applications.

Acknowledgements

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