Progress and development in Fibre Laser technology

Ray Horley, Stephen Norman and Michalis N. Zervas (*)
SPI Lasers UK Ltd, Southampton, UK;
(*) also with Optoelectronics Research Centre, University of Southampton

ABSTRACT

High performance fibre lasers are now well established as an extremely robust and reliable technology enabling a growing and diverse number of demanding industrial and medical and applications. Compared to rival technologies, such as carbon-dioxide (CO_2), Lamp/Diode-Pumped Solid-State (L/DPSS) and disk lasers, fibre lasers offer a number of unique characteristics that have resulted in their wide adoption in an increasing number of industrial sectors. In addition to replacing conventional lasers in existing applications, fibre lasers have been very successful in enabling new applications, both factors which explain their increasing market share. In this paper we describe the basic features of fibre lasers, and discuss their generic advantages compared with other laser technologies and consider how these may translate to defence applications. We explain our proprietary cladding-pumping technology (GTWave^{TM}) and the laser architectures we use to implement our commercial products. We present parametric performance data that show the vast range of pulse waveforms that can be produced and discuss some new industrial applications that they have recently enabled. Finally, we reference some of the leading research results for multi-kW continuous-wave (CW) fibre lasers and summarise SPI's published work in this field.

Keywords: high power, fibre laser, MOPA, cutting, welding, marking, pulse, defence

1. INTRODUCTION

In this section we provide a general introduction to fibre lasers, considering advantages over other laser technologies that make them leading candidates for defence applications.

1.1 Fibre Laser features

Figure 1 illustrates the key features of a fibre laser. This is an extremely elegant structure in which all of the required elements of the laser are incorporated into the fibre itself.

The power source for the laser is a collection of semi-conductor pump diodes. These come in many forms, including single-emitter diodes, diode bars and stacks, or even fibre lasers. They can be coupled to the fibre by a variety of means, including end and side-pumping. One can achieve end-pumping with free-space optics (suitable mainly for research) or commercially-available tapered fibre bundles (TFBs). We will describe our side-pumping approach in the next section, which is pivotal in ensuring the reliability and robustness of a fibre laser for commercial use.

The inner cladding of the fibre is a highly multi-mode waveguide that guides the pump along the length of the device, permitting coupling to the fibre core. The waveguide is formed by a low-index outer-cladding that can be a polymer coating, a solid glass or a micro-structured fibre.

The core of the fibre is conventionally a rare-earth doped solid core that absorbs the pump radiation and provides optical gain to produce laser emission. It is often a single-mode waveguide that can be fusion-spliced to fibre-integrated Bragg Gratings (FBGs) that form the resonator cavity of the laser. It could also be a multi-mode waveguide, more commonly applied in a fibre amplifier configuration. Either way, the active process of energy-conversion from the pump to the signal transforms the relatively low-brightness (and therefore low-cost) pumps sources into a very high-brightness beam.

Technologies for Optical Countermeasures IV, edited by David H. Titterton, Mark A. Richardson
Proc. of SPIE Vol. 6738, 67380K, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.753171

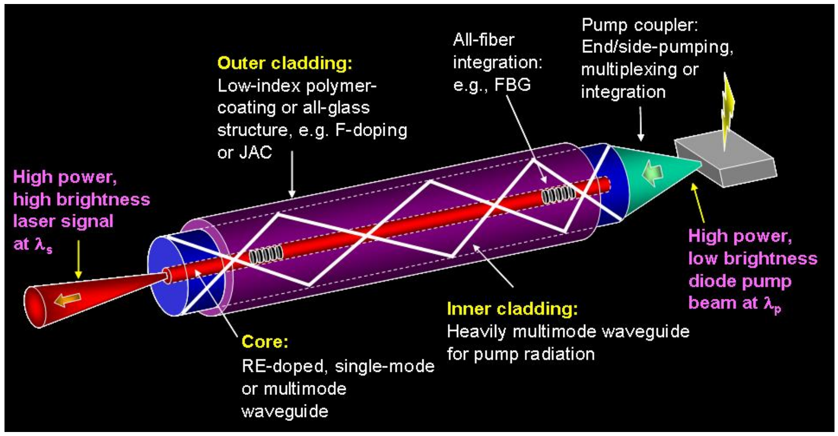


Figure 1: Schematic illustration of the key elements of fibre lasers

1.2 Generic advantages of Fibre Lasers

Fibre lasers offer significant advantages in terms of their optical performance, robustness and operational benefits. They benefit from an all-fibre, all-guided architecture, which makes them robust and reliable. They display no thermal lensing effects, which results in excellent beam pointing stability compared to conventional lasers. They are unique in offering instant turn-on operation without regular tuning and re-alignment. The inherently large surface-to-volume ratio facilitates heat removal and minimises external cooling requirements. The beam quality can be engineered by proper fibre core design to match the application requirements.

Fibre lasers are usually pumped by combining a number of extremely robust, telecommunication-grade, single-emitter broad-stripe multimode pump diodes. This results in laser systems with long lifetime, maintenance-free operation. In addition, due to the very low loss, monolithic all-fibre geometries, they have superior optical-to-optical, electrical-to-optical and overall wall-plug efficiencies. Finally, fibre lasers have a very small and compact footprint that facilitates their system integration.

1.3 Advantages for defence applications

The diffraction-limited beam quality and superior beam-pointing stability have wide benefits in defence applications, including the ability to deliver power at long range with small spot sizes, in single or coherently-combined beams, for directed energy. It is well known that this places other parametric requirements on the fibres, such as polarisation-maintaining properties and the ability to amplify low-power, narrow linewidth sources to very high powers. The output power can be limited by non-linear effects in the fibres, and research by many teams is being targeted to alleviate this. SPI's published work in this area is reviewed briefly in section 4.3.

Many types of electro-optic sensor and optical countermeasure require operation at specific wavelengths that are not necessarily essential in the industrial space. Fibre lasers can provide an extended range of optical wavelengths either by direct emission and/or wavelength conversion. Direct emission can be achieved between about 1 and 2μm by using different active dopants, for example ytterbium, erbium, erbium-ytterbium, neodymium, thulium and holmium. The longer wavelengths are described as "eye-safe", important for reducing the risk of injury to anyone exposed to the laser radiation. SPI already has a 1.5μm fibre laser product, with 20W output power.

Wavelength conversion can be provided within the fibre itself, using optical non-linearities such as Raman scattering, or via external means. For example, visible and ultra-violet (UV) wavelengths can be produced by frequency doubling, tripling or quadrupling, which again require polarised 1μm and 1.5μm sources; all achievable in fibre.

The non-linear effects referred to above can present a challenge for the realisation of pulsed laser sources with high pulse energies, as required for optical countermeasures. We anticipate significant levels research to expand the performance envelope of fibre lasers still further, and studies into the utility of existing technology, to permit their wider adoption for defence. The practical advantages of fibre lasers make them leading candidates for defence use. In particular, their robust construction makes them ideal for deployment in harsh environments, and their unrivalled efficiency will reduce weight and volume, for which there are stringent requirements for incorporation in military platforms.

2. METHODOLOGY

2.1 SPI's side-pumping technology

Key to harnessing the benefits of an all-fibre laser configuration is the adopted pump-coupling scheme. All SPI's laser products use a proprietary cladding-pumping technology (GTWave^{TM}) that enables multi-port, distributed pump injection, facilitates output power scalability and ensures system reliability, longevity and maintenance-free operation. This approach is illustrated in Figure 2.

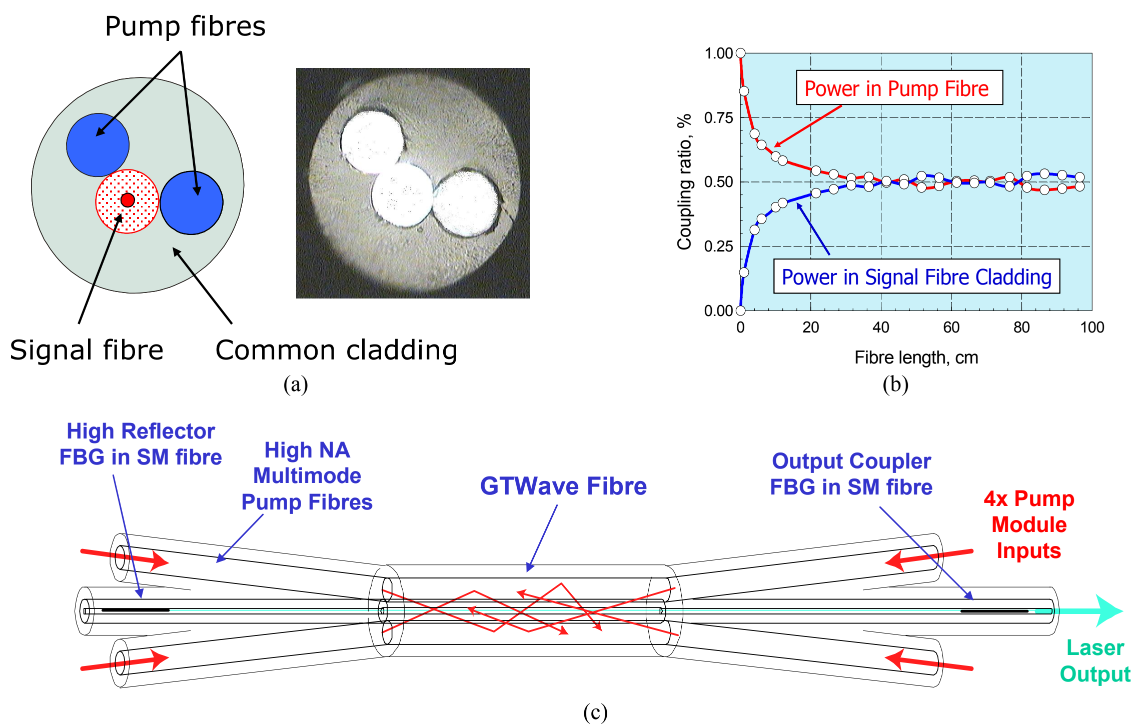


Figure 2: GTWave side-pumping technology; (a) Schematic diagram and optical micrograph of GTWave fibre cross-section, showing signal and pump fibres in a common low-index, pump guiding coating, (b) graph showing the distributed nature of the pump coupling between the pump and signal fibres and (c) side view of GTWave fibre laser, with pump injection ports, FBGs forming the laser cavity and fibre-delivered output

Figure 2(a) provides a schematic diagram and an optical micrograph of the GTWave fibre cross-section, showing one signal and two pump fibres in a common low-index coating. The claddings of the signal fibre and the pump fibres are analogous to the inner cladding in Figure 1; the common coating is analogous to the outer cladding.

When pump radiation is coupled from the diodes into the GTWave fibre (by fusion-splicing the diode output fibres to the GTWave pump fibres), it is coupled across to the signal fibre in a distributed manner. Figure 2(b) illustrates this by plotting the coupling ratio for pump radiation between the pump and signal fibres (for a variant of GTWave fibre with only one pump strand). The distributed nature of the pump scheme is vital for reliable laser operation. Even a few percent of loss at a single point could lead to several Watts of heat dissipation occurring in a localised region. "Single-point" injection techniques, such as end-pumping or "V-groove" side pumping, can thus result in "hot spots" and premature product failure. In contrast, the distributed pump coupling in GTWave occurs along its entire length, avoiding "hot spots", and thereby facilitating output power scalability.

Figure 2(c) provides a schematic representation of a GTWave fibre laser. The bold red arrows indicate the pump injection ports and the finer arrows symbolise the coupling of the pump radiation into the signal fibre inner cladding, where is it subsequently absorbed by the core. Fibre Bragg gratings (FBGs), exposed in single-mode fibre and spliced to the signal fibre of the GTWave, form the laser cavity. The laser output is delivered by another fibre, attached to the right of the output coupler FBG, and thus we see that all critical functions of the laser are implemented in fibre.

2.2 Laser configuration

Taking the components in Figure 2(c) and adding fibre combiners to aggregate the output of many pump diodes, fibre tap-couplers and photo-diodes for signal and back-reflection monitoring, and a beam collimator, we have the essential optical elements of the fibre laser configuration. This is used in SPI's CW/Modulated (CW/M) redPower^{TM} fibre laser products rated between 10 and 100W.

2.3 Master-Oscillator Power Amplifier (MOPA) configurations

As we have seen, GTWave fibre can have many pump fibres, generating multiple pump injection ports. This is one way to scale the power of fibre lasers, however the GTWave signal fibre ends remain free for further splicing, enabling the cascading of several units without obstructing the signal optical path. The fibre laser can then act as the Master Oscillator (MO) in a MOPA configuration in which other GTWave stages act as Power Amplifiers (PA). This robust, modular approach adds enormously to the efficient power scaling potential of GTWave, and is used in 100-400W CW/M products at 1μm wavelength.

The MOPA configuration has also been applied to SPI's pulsed lasers (Figure 3). Optical fibres, being extremely high gain media (>50dB small-signal gain per stage) can adequately compensate for their inherently reduced capacity to store energy and can provide high performance pulsed systems. SPI's redEnergy^{TM} products exhibit pulsed operation with energies in the range of 0.8mJ and peak power in excess of 15kW, at 25 kHz repetition rate. The output wavelength is in the 1μm range, and it is possible to produce similar devices at 1.5μm.

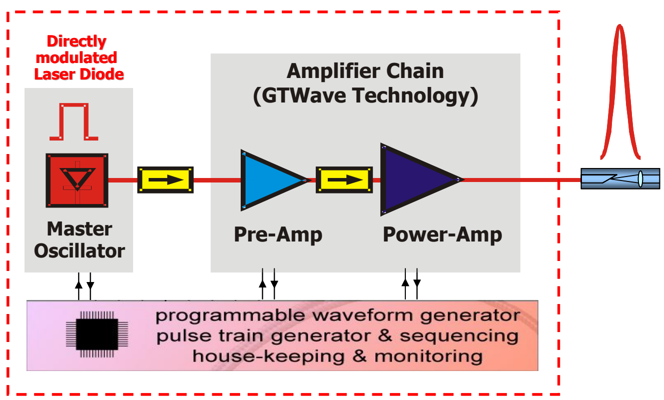


Figure 3: MOPA configuration based on GTWave technology for pulsed fibre lasers

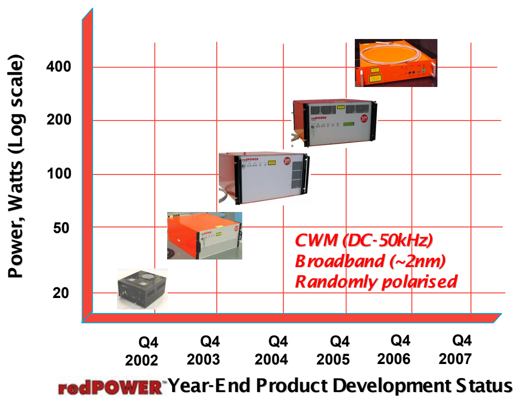
At the very high CW and pulse peak powers attainable in these MOPA devices, efficiency degradation due to photo-darkening can occur. All SPI's active fibres are designed to be photo-darkening free, adding into system reliability and longevity.

3. PERFORMANCE DATA

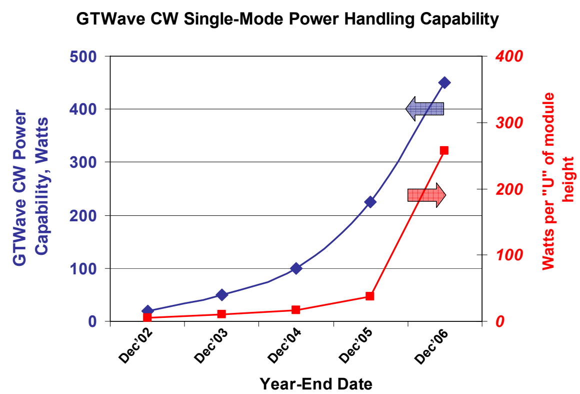
3.1 CW/M Fibre Lasers and MOPAs

Figure 4 summarises SPI's CW/M fibre laser product evolution and Figure 5 summarises some key performance parameters. Figure 4(a) shows the annual doubling in output power demonstrated in these products, while Figure 4(b) expresses this in terms of the GTWave fibre power capability in absolute terms and as a function of the height of the laser module. SPI has made significant reductions in the volume of fibre lasers over recent years, further distinguishing them from other laser technologies in this regard.

Fibre laser power characteristics are generally extremely linear, often only limited by the pump power available. Figure 5(a) shows the typically linear characteristic of the 400W fibre laser module and 5(b) shows the beam quality measurement at 400W. This data is invariant with power and shows that the beam is single-moded with a quality parameter $M^2<1.1$ over the entire operating range.

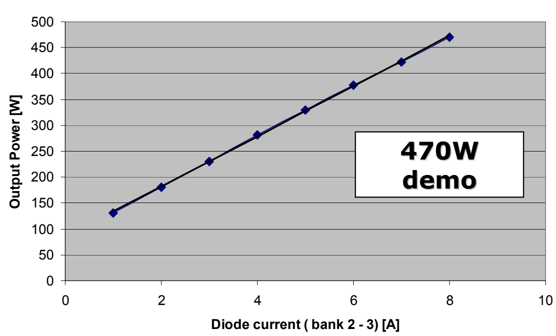


(a)

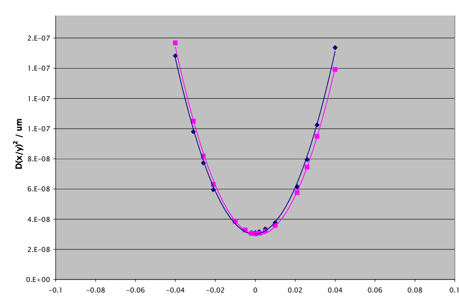


(b)

Figure 4: (a) Annual doubling in the output power demonstrated in SPI's redPower™ CW/M fibre lasers, on a logarithmic scale, (b) GTWave power capability by year; in absolute terms and expressed as a function of the laser module height



(a)



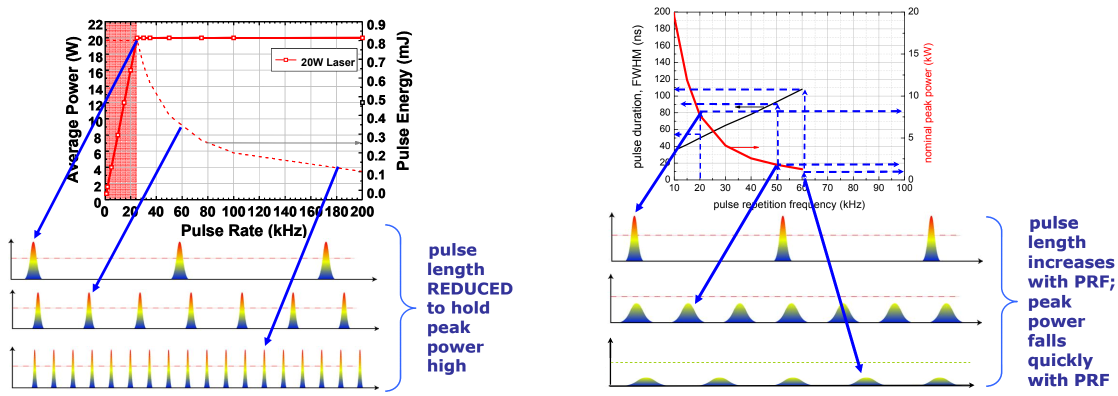
(b)

Figure 5: (a) Highly linear power characteristic of the 400W fibre laser module and (b) beam quality measurement at 400W, showing that $M^2<1.1$ over the entire operating range

3.2 Pulsed Fibre Lasers

Figure 6(a) illustrates the performance capabilities of a SPI's MOPA-based pulsed fibre lasers, which offers an excellent combination of beam quality (M^2<2), and controllable pulse repetition rate, peak power, and pulse energy, over an exceptional operating range. The module's average output power of 20W is shown in use across a broad parametric window, from "high-energy" pulses of 0.8mJ per pulse at 25 kHz repetition rate, to "low energy, high-speed" pulses of 100uJ per pulse at up to 200 kHz. In fact, recently the operating window has been further widened to produce 40µJ per pulse at a state-of-the-art repetition rate of 500 kHz. The corresponding peak powers are typically ~15-20kW at the "high-energy" end and >1kW at the "high-speed" end.

This performance with sustained high-peak power over a broad range of repetition rates cannot be matched by Q-switched lasers (of equivalent power and size), whether DPSS or fibre-based. With the Q-switched laser design, increasing the pulse repetition above a certain rate leads to pulse collapse, substantial pulse width increase and peak power decline. This behaviour is illustrated in Figure 6(b).



(a) (b)

Figure 6: (a) Pulse peak powers are maintained at the same level in SPI's MOPA-based pulse laser, whereas in (b) pulses collapse in Q-switched lasers.

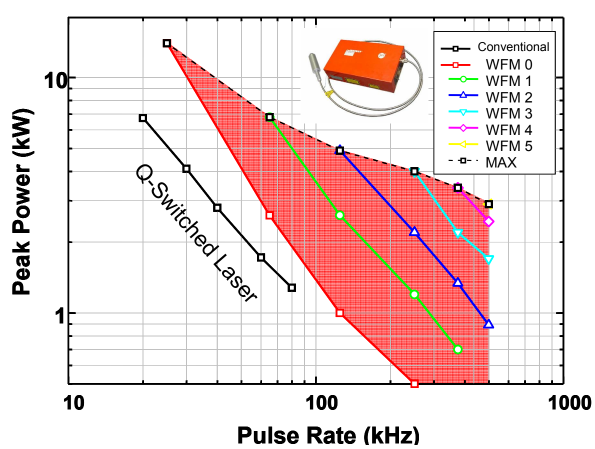


Figure 7: Large operating window for SPI's pulsed lasers, compared with the limited range of Q-switched lasers

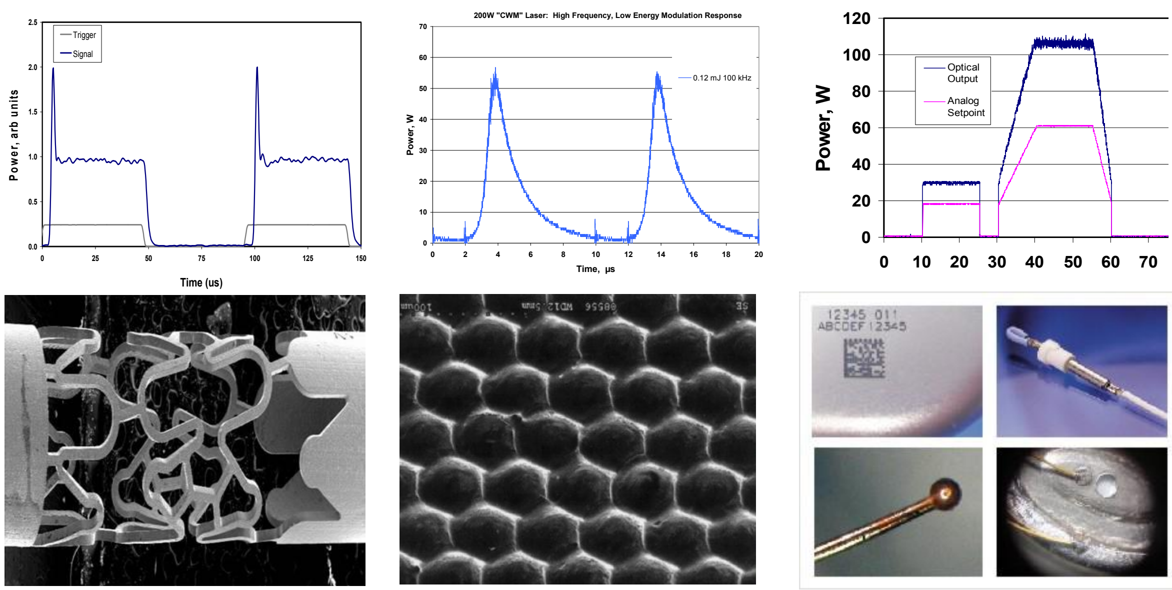
Figure 7 compares the broad operating envelope for SPI's MOPA-based pulsed lasers shows that this technology can produce peak powers in excess of 3kW for repetition rates up to 500 kHz. It also shows that conventional "inflexible" designs, where pulse shapes and repetition rates are mutually dependent, provide comparable performance only up to 40 kHz. Such performance differences can result in a ten-fold increase of process throughput in industrial applications, and SPI is very interested to learn how this flexibility can be exploited in defence applications.

4. APPLICATION RESULTS

4.1 CW/M Fibre Lasers and MOPAs

SPI's high power fibre lasers are used in a number of industrial and medical applications, including stent tube cutting, disc drive spot welding, electronic stencil cutting, ink transfer-plate engraving for printing, rapid manufacturing and medical aesthetics. Many of these exploit the almost limitless flexibility in output pulse characteristics that can be produced using the modulation capabilities of the CW/M fibre lasers. During the last year, new applications have been enabled by these products, including automotive plastic welding, medical piece part welding, silicon cutting, alumina cutting and scribing and plastic cutting.

Figure 8 shows examples in which pulse waveform have been designed for specific applications, such as; (a) high-precision cutting of arterial stents, (b) ink transfer-plate engraving and (c) fine welding. The last has most recently been applied to implantable medical devices. Much longer pulses are used for welding; the time-base for Figure 8(c) is ms, whereas it is μs for Figures 8(a) and (b).



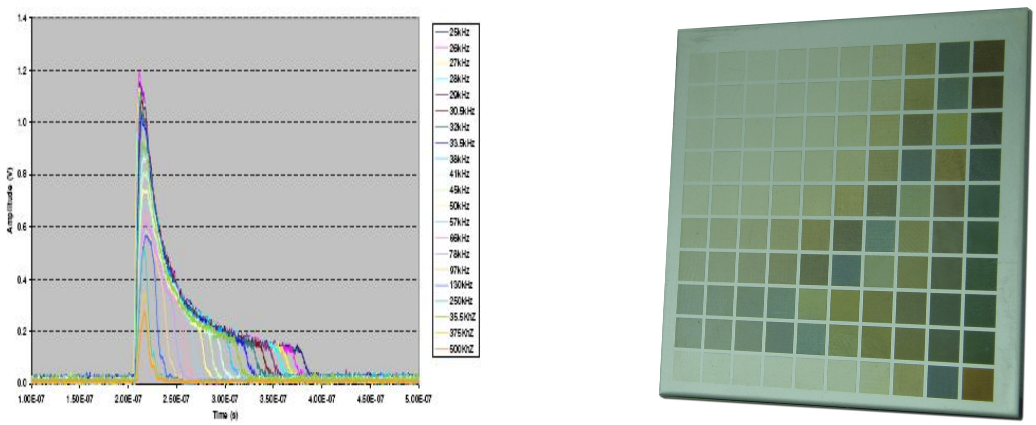
(a) (b) (c)

Figure 8: Specifically designed pulse waveforms generated by SPI's CW/M fibre lasers for (a) arterial stent fine-cutting, (b) ink transfer-plate engraving for printing, and (c) welding of implantable medical devices

4.2 Pulsed Fibre Lasers

The pulsed fibre lasers are generally used for marking applications, which fall into a vast array of categories, given the extensively broad operating window. The "high-energy" pulses (0.8mJ per pulse achievable at 25 kHz repetition rate) are ideal for marking hard metals, while the "low energy" pulses around 40uJ per pulse are suitable for high-speed marking onto polymer substrates. At this pulse energy, the laser can deliver pulses at 500 kHz repetition rate, dramatically increasing process throughput. The same laser module can be operated in CW-mode and power-modulated for bitmap marking applications.

More recently, SPI has extended the application range of the pulsed fibre laser to IC and polymer marking and thin film ablation[1] and colour marking of stainless steel[2]. This last application epitomises the comprehensive pulsed fibre laser capabilities, as it produces a spectacular range of surface properties through precise pulse energy and repetition rate control. Figure 9(a) shows the newly-introduced 20 waveform feature set that enabled the fabrication of the colour palette shown in Figure 9(b).



(a) (b)

Figure 9: (a) 20 waveform feature set of SPI's pulsed laser, offering precise pulse energy and repetition rate control to produce (b) a "colour marking" palette on stainless steel

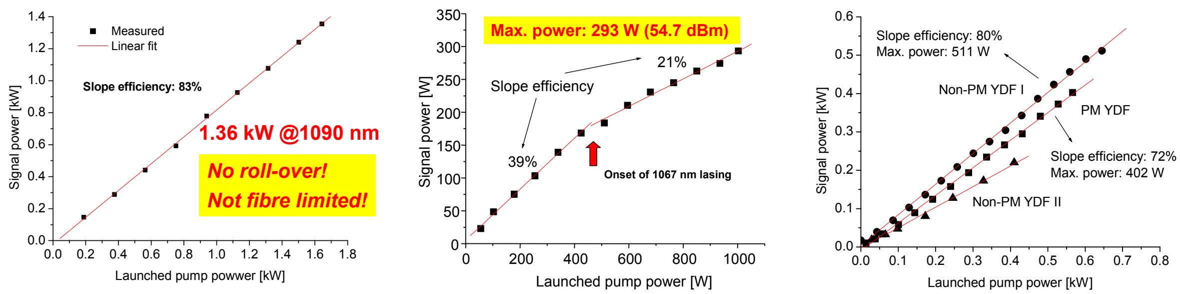
4.3 Very high power CW Fibre Laser research results

There is a strong and continued interest in scaling the output power of CW fibre lasers further for "macro-industrial" (e.g. automotive and white-goods cutting and welding) and defence (e.g. directed energy) applications. Several groups are currently working on power combination and power scaling to multi-kW levels. The leading published result for a single-mode broad-band CW fibre laser is 3kW[3], and simple considerations of the expected thermal load and fibre optical damage threshold suggest this can be extended to 10kW. This, however, will require the development of brighter pump diodes and special active fibres to enable precise modal control and suppress optical nonlinearities.

SPI, working closely with the Optoelectronics Research Centre at the University of Southampton (ORC), has published world-leading research results in this area[4, 5, 6]. These are summarised in Figure 10. Figure 10(a) shows the culmination of programme of work that produced the world's first kW fibre laser. At this time 1.36kW was demonstrated with single-mode beam quality, at 1.1μm wavelength. Subsequent work (unpublished) has significantly increased the output power further.

Figure 10(b) shows the world-leading results at 1.5µm, in which 180W was demonstrated with high efficiency. Above that power level, parasitic emission at 1.1µm reduced the slope efficiency but it was still possible to achieve nearly 300W in this experiment. Further work to eliminate this effect is planned.

The results above were achieved with an end-pumped fibre laser configuration, using 976nm diode-bar pump sources. When the 1.1µm arrangement was modified into a MOPA configuration, high-gain amplification of narrow-linewidth, polarised signals could be achieved. Figure 10(c) summarises the performance of three MOPAs, two non-polarised ("non-PM YDF") and one polarised ("PM YDF"); in this figure, YDF stands for "Ytterbium-Doped Fibre". The non-polarised MOPA was able to produce 511W before stimulated Brillouin scattering (SBS) limited the output power. The polarised MOPA produced 402W before the same limitation occurred. Work is underway to improve these results.



(a) (b) (c)

Figure 10: Key results from SPI and ORC published research on very high power fibre lasers and MOPAs (a) 1.36kW single-mode single-fibre laser at 1.1µm, (b) 293W single-fibre 1.5µm fibre laser and (c) 511W non-polarised fibre MOPA and 402W polarised fibre MOPA, both with narrow linewidth

5. SUMMARY AND CONCLUSIONS

In this paper we have described the basic features of fibre lasers and discussed their performance and reliability advantages over traditional laser technologies. We have explained the GTWave™ technological approach we use to build all of our products and illustrated how this can be configured in laser and MOPA formats. We have seen that GTWave lasers and MOPAs can produce CW/M laser products from 10-400W at 1µm wavelengths and 20W at 1.5µm, all with diffraction limited output beams. GTWave pulsed lasers using the MOPA architecture operate at up to 20W average output power ($M^2<2$) with a rich variety of pulse parameters that cannot be equalled with Q-switched lasers.

We have seen that both the CW/M and pulsed lasers can produce a vast range of pulse waveforms that are already in use for a wide variety of industrial applications. Recently this range has been expanded to include automotive plastic welding, medical piece part welding, silicon cutting, alumina cutting and scribing and plastic cutting (CW/M lasers) and IC and polymer marking and thin film ablation and colour marking of stainless steel (pulsed lasers). Finally, we reviewed some of the research work conducted on multi-kW fibre lasers that is relevant to macro-industrial and directed-energy applications.

Whilst the majority of our experience is in the development and manufacture of fibre lasers for industrial and medical applications, we expect many of the advantages of fibre lasers to translate across to defence applications. In particular, their robustness makes them ideal for field-deployment and their unrivalled efficiency could be decisive in meeting stringent weight and volume requirements. Add to that, diffraction-limited beams with superior pointing stability, polarisation-maintaining properties, high-gain amplification, a range of emission wavelengths, and almost unlimited control over pulse parameters, there are many reasons to anticipate their widespread adoption in defence applications.

REFERENCES

[1] A. Hoult, “High Precision Laser Marking with novel nano-second pulsed MOPA Fibre Lasers”, Proceedings of the Fourth International WLT-Conference on Lasers in Manufacturing 2007, Munich, June 2007

[2] S. Norman and M. Zervas, "Fibre Lasers prove attractive for industrial applications," Laser Focus World, August 2007

[3] V. Gapontsev, “3kW single-mode output at ~1µm from a Yb-doped fibre MOPA”, Photonics West 2007.

[4] Jeong, J. Sahu, D. Payne, and J. Nilsson, "Ytterbium-doped large-core fibre laser with 1.36 kW continuous-wave output power," Opt. Express **12**, 6088-6092 (2004)

[5] Y. Jeong et al., “293 W “eye-safe” output at 1567 nm from an Er:Yb co-doped fibre laser” OFC 2006, OTHJ7

[6] Y. Jeong, “400 W single-frequency, single-mode, plane-polarized output at 1060 nm from a Yb-doped fibre MOPA”, CLEO-EU 2005, TFII1-1-WED