Not just another laser platform

Quo Vadis Fiber Lasers

Fiber lasers have been a hot topic in laser conferences and industry meetings for several years now, and are finally starting to appear en masse in the market place. Currently the industrial fiber laser market is in practice completely dominated by IPG, which is enjoying strong growth and now poised for an IPO. In this article we seek to provide a big-picture perspective on fiber lasers, the underlying technologies, the commercialization challenges, and the changes in the market fiber lasers are likely to bring about.

Lasers, although already an old invention, have throughout their existence continuously developed due to new technologies. While it is fair to say that current workhorses such as CO_2 lasers and lamp pumped solid state (LPSS) lasers have reached maturity, laser technology development in recent years has been more active than ever. In addition the rate of performance improvement seems to be increasing over the last five years as fiber laser technology has driven CW power scaling, wall-plug efficiency and beam quality to new heights. Although there are already a lot of laser technologies available on the market, including CO_2, LPSS, diode pumped solid state (DPSS), direct diode lasers and disk lasers, fiber lasers are poised to open a new era in the laser market – in terms of performance but even more importantly in terms of cost. However, unleashing the potential of fiber lasers is not easy; this is a laser technology more sophisticated than ever before, with heavy investments required in the underlying manufacturing machinery, and with currently only a few companies in the world capable of providing fiber lasers or components. To make a complete fiber laser requires an advanced diode fab and packaging, a state-of-the-art fiber facility, and advanced equipment to manufacture components like gratings, combiners and isolators. The investment is high, as is the time required to make this investment productive with a stable process.

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Fibers: what is different?

As such fiber lasers are just like any other lasers – they have a cavity, a gain region, and require a pump source, and all components must be accurately integrated. Some differences exist, for example the cavity mirrors are formed by “fiber Bragg gratings” (FBGs), periodic structures created into a piece of fiber, rather than conventional mirrors. Another difference is that the entire laser structure, including active and passive components, can be fused into a continuous fiber harness. This monolithic structure makes the system very robust against any external factors, and is adjustment free. However, just like cavity alignment in solid state laser manufacturing, assembling a fiber laser cavity needs care. The process of joining fibers, splicing, is the equivalent of the cavity alignment and requires high precision tools and trained operators. Like in other laser technologies, all components in the fiber laser system must meet very stringent quality requirements and need to be made by companies with experience in mass-production and good quality management. This is very analogous to the processes instituted in the bulk optics industry.

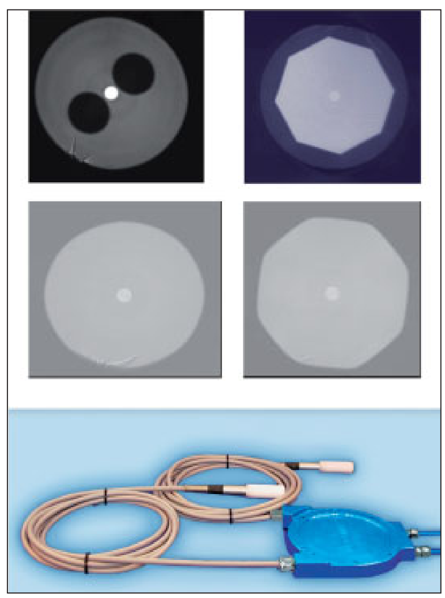


FIGURE 1: **Top: today fibers can be made in almost arbitrary shape with highest precision. Bottom: Fiber lasers are highly integrated, completely encapsulated systems, tolerant to vibration, dust and temperature changes.**

Fiber laser characteristics

Much has been said about the benefits of fiber lasers. While there may be some controversy about some of the benefits and their implications in specific applications, there is universal agreement on the basic characteristics:

- **Life Time:** Fiber lasers can be built on telecom grade components, which guarantee a long lifetime. Thus, for example, the pump diodes can have life times over 100 khours (single emitter structures).
- **Robust:** fiber lasers (including the associated pump diodes) are inherently monolithic, which makes them both robust as well as requiring very little maintenance.
- **No Large Chillers:** Thermal management is relatively straightforward due to large surface ratio (and efficiency) and thus large chillers and complicated cooling mechanisms can be avoided. This also applies to the pump diodes, especially if single emitter structures are used.
- **High Efficiency:** Fiber lasers provide excellent efficiency (both optical and wall plug efficiency) and also very high gain.
- **Stable Beam Quality:** Fibers provide both gain and mode guiding for the photon field, which makes it possible to achieve very bright laser output without sacrificing robustness of the system. The mode guidance of the fiber ensures that the beam quality is independent of the output power.
- **Tunable:** Due to the large gain bandwidth of ions in glass, fiber lasers are tunable in the frequency domain. The large gain bandwidth also makes them suited for pulsed applications, even ultrashort pulses. Using MOPA (master oscillator-power amplifier) structures the repetition rate of pulsed fiber lasers can be widely tuned without sacrificing pulse energy or beam quality. As a drawback, the active gain volume is relatively small, which limits achievable pulse energies somewhat.
- **Many Wavelengths:** Fiber lasers are available in the 1 µm regime using Ytterbium (Yb) and Neodymium (Nd) doped active fibers, as well as at 2 µm (Thulium, Tm) and 1.5 µm (Erbium, Er). Furthermore, Raman lasers offer access beyond the atomic bands of Nd, Yb, Er, and Tm, and co-doping allows pumping for example at the Yb band, while providing gain at the Er band.
- **Random Polarization:** One of the limitations of current high power (several kW) CW fiber lasers is that their output is randomly polarized rather than linearly polarized like many other lasers. This is an engineering challenge that may play an important role in thick material cutting.

Where to buy a fiber laser?

Fiber laser performance has been demonstrated in many scientific papers, and leading research groups from ORC/Southampton University, Prof. Tünnermann's group in Jena, University of Michigan, Sandia National Laboratories (and many others) have achieved stellar results. However, to be fair, commercializing fiber lasers has proven fairly difficult, with few companies succeeding so far. IPG has certainly managed to provide convincing results over the past years in taking the fiber laser technical benefits to the customer premises. Customers using IPG 5–7 kW systems have reported as promised performance in international conferences. IPGs low power pulsed lasers, for example the 10 W 0.5 mJ unit, are replacing earlier LPSS lasers due to better performance, smaller size and minimal maintenance, and are quite widely deployed in marking applications.

FIGURE 2: **Fiber laser manufacturing needs not only high investment but also much time to establish the know how for precise control of the manufacturing process.**

SPI is starting to establish a reputation and presence with its CW lasers in fine materials processing (100 W module on the market for some time now), and is likely to extend its reach further with its new 200 W CW laser and family of pulsed lasers in the 10–20 W

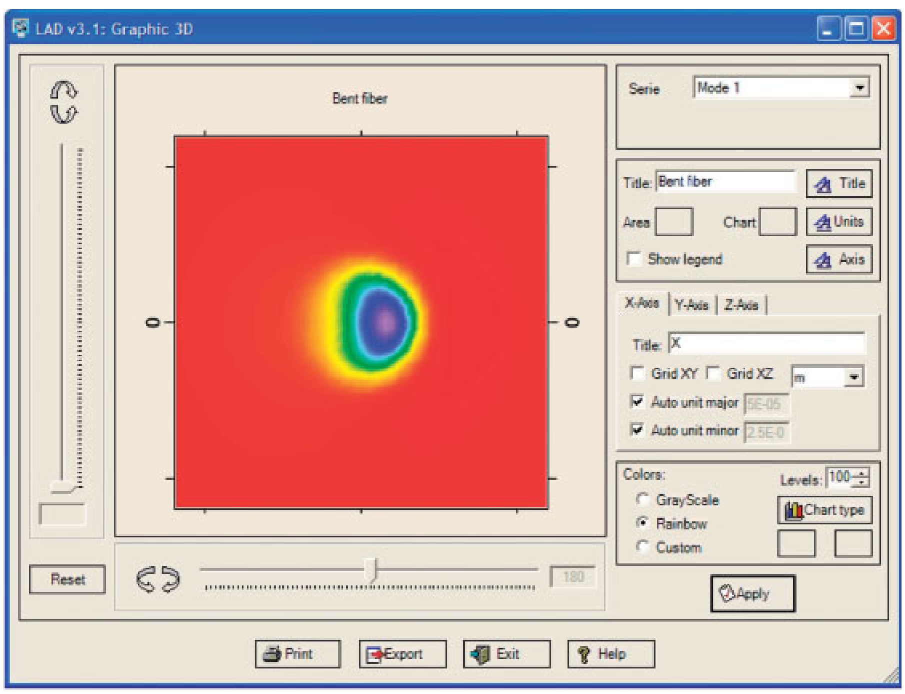


FIGURE 3: **LIEKKI has developed its own fiber and application design software.**

COMPANY

Liekki Corporation

Founded in 1999, Liekki today employs 35 people, including many PhDs. The company produces high performance fibers, as well as fiber components and subassemblies ("optical engines"). Liekki also offers design software and engineering support to its customers, who include most fiber laser and telecom manufacturers worldwide.
The company's HQ and production plant are located within the Helsinki area, while the Liekki Inc. subsidiary is in the USA. Liekki holds 13 patents and over 25 patent applications.
www.liekki.com

(average) power regime. Though IPG clearly dominates the major markets setting the performance and price standard, we can expect SPI and others to follow. It should also be noted that JDSU has had a fiber laser solution for marking applications on the market for several years, although it is not fully clear they will continue with fiber lasers.

Companies like Miyachi and Hamamatsu are also making progress in bringing fiber laser technology to the market, and we can expect other incumbents to enter over the next few years. Besides the bigger players in the main markets, several smaller players are targeting more specific niches with interesting products, including, for example, pico- and femtosecond lasers for microprocessing and other demanding applications (consider for example the laser and amplifier products of companies such as Calmar, Clark MXR, Corelase, Fianium, IMRA, Keopsys, Menlo Systems, Mobius, MPB, Multiwave, NP Photonics, Nufern and Pritel, to mention just a few). So, while fiber lasers are still early in terms of entering the mainstream, it seems we will see plenty of commercialization activity over the next years.

Fibers reach further: the markets

Driven by well-attended presentations at key industry conferences, much of the discussion about fiber lasers is focused on whether or not a certain performance characteristic is better than that of another laser technology (such as disk, solid state/rod, or gas). While such debate certainly is important it misses a key point, namely the wide applicability of fiber laser technology, and the underlying scalability and volume economics.

CO_2 gas laser technology, the workhorse of high power CW lasers, is primarily applied in industrial manufacturing lasers, and in particular in cutting and welding. In some cases high power solid state lasers (rod and disk) have found a market in industrial manufacturing too, due to their capability of providing a fiber coupled output beam. In addition solid state lasers, be they LPSS or DPSS, are widely used in marking applications, and in high end applications used in semiconductor industry, medical and scientific markets. Companies in the military, security and aerospace sectors employ solid state technology, often new DPSS configurations like slabs and disks, but also other laser technologies. However, none of these technologies have gained a foothold in an important market: telecom. It is fair to say that currently each laser market sector is served by a specific technology, and

INTERVIEW

LASER TECHNIK JOURNAL: *Dr. Stenius, what is your recipe for success in the fiber laser business?*

Per Stenius: Our advantages are the unique DND technology to make superior fibers, our fiber assemblies and our foothold in all key markets for both lasers and telecom. We also have a strong patent portfolio, and have been careful in licensing the additional IP required. Being a components supplier brings challenges – we often must support clients beyond our products to help create a complete solution (laser, amplifier or laser system). Liekki's success comes from offering innovative products with better performance, providing these products at very attractive prices, and helping the customer develop complete solutions.

LTJ: *Do you think fiber lasers will outperform "conventional" systems and take a dominant market position?*

Per Stenius: This seems reasonable – at least in the major sectors driven by lifecycle cost. This is not about performance alone – economics are crucial. The fiber laser platform (including high brightness pump diodes) can address the needs of all major markets (industrial, medical, military, scientific and telecom), quite unlike any previous laser technology. Fiber lasers are cost effective, scalable and modular. They form highly reliable monolithic solutions, require little maintenance and are easy to use. All this spells success for fiber lasers at a deployment scale larger than achieved by any other laser technology so far.

LTJ: *Is the dominant position of a single player like IPG advantageous for the market success of the fiber laser technology?*

Per Stenius: This is a difficult issue. Has Microsoft's position been advantageous for the proliferation of PCs? One can argue for and against. Dr. Gapontsev and his team have achieved much by having pioneered fiber technology and products earlier and faster than anyone expected. IPG continues to lead by focusing on markets where fiber lasers offer a performance and usability advantage while promoting aggressive pricing unparalleled in the industry. But the market will get much more competitive in the next 2–3 years. New entrants and incumbents will be offering attractive alternatives to increasingly demanding customers. It is still too early to say whether IPG can capitalize on its current position and secure a long-term dominant position.

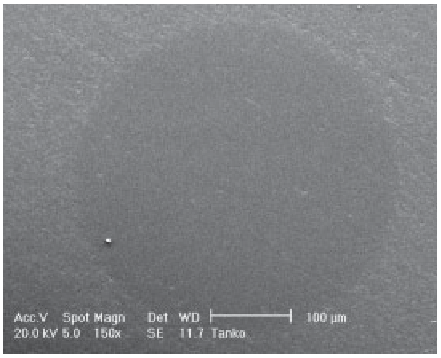
LTJ: *What do you see as the main barrier to customers buying fiber laser instead of other solid state lasers now?*

Per Stenius: Fiber lasers are an emerging technology. We are now between the early adopters and the mainstream. Mainstream users, being conservative, usually want to see more track record and are often willing to wait longer to see how the early adopters fare. Thus in many markets the main barrier is the customers' own attitude towards new solutions. Many potential users – especially those requiring high end laser tools – are taking a wait-and-see approach and are content to let competitive dynamics resolve which technology wins. And even price is an important barrier – customers want better performance and easier-to-use lasers at a lower price than ever before.

LTJ: *How would you overcome these obstacles?*

Per Stenius: The way IPG and SPI are working seems to be effective. The product price must be competitive, it starts there. Collaborating with research institutes to develop application knowledge and parameters helps too. Application labs and test units for customer use are the next steps.

We are following a similar path. Liekki offers great components at a competitive price every day. To achieve this, we use the latest flexible manufacturing approaches with Six Sigma, increased automation and product platform design. Our DND fiber manufacturing process fits well here. DND allow: preform assembly from separate core, cladding and stress rod elements; platform design is built into DND. However, this is not enough. Design-to-cost work with clients is essential, as is collaboration with leading research institutes. We work with partners such as the Fraunhofer Institutes, Tampere University, Technical Research Centre of Finland, and Sandia National Labs in the USA. We maintain a long-term approach in all we do.



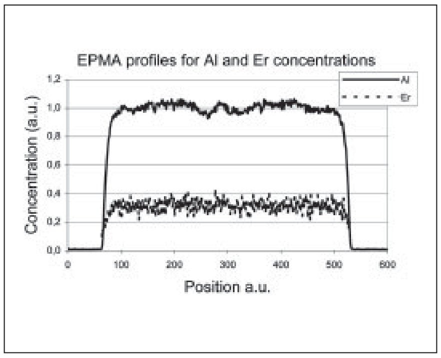


FIGURE 4: **Precise doping is crucial for fiber performance. Left: Cross section of the core of a LIEKKI fiber. Right: Doping profile across the fiber core showing highly homogeneous doping.**

that there are limited technology synergies across the sectors. This also implies that each laser technology only sees a limited part of the overall laser market.

Fiber laser technology changes this completely. Fiber lasers have been successfully deployed in all market sectors mentioned above, and many more. In addition, in many cases (for example, large scale welding at shipyards or pipeline building, military applications such as minefield clearing, and handheld laser tools used in structural cutting and surface cleaning) fiber lasers have opened up completely new markets. When lower beam quality is enough, the pump diodes can be used to make direct diode laser systems. Furthermore, fiber laser technology (using single emitter diodes) applies to telecom, and IPG has shown that this can be done quite successfully (over 15% of IPG's revenue comes from telecom). The key point is that fiber lasers deployed in all these different markets use common components, capturing economies of scale like never before. This is precisely what IPG does; its success is testimony to the strength of a vertically integrated strategy addressing multiple markets simultaneously.

Pushing fiber lasers to many markets has led to another advantage: simplicity. Once the lasers are assembled, no more "setup" is required, making the deployment of fiber lasers less resource consuming. Early users, such as TWI in UK, report that multi-kW fiber lasers are essentially "plug-and-play", making the startup process a matter of hours rather than days.

To summarize fiber lasers (and direct diode lasers built using pump diodes) have wide applicability to many markets, the manufacturing of fiber lasers and underlying components shows economies of scale, and the deployment of fiber lasers ties-up less resources in terms of installation, system startup, and maintenance. Essentially, fiber lasers form a platform technology providing a very cost effective and scalable base across market sectors. Looking again at IPG: their faster-than-industry growth can only be driven by the platform nature of their fiber and diode technology applied across markets. By simultaneously addressing all major laser market sectors (including telecom) globally, fiber laser technology is a paradigm change not only in performance but also in the business model of lasers and laser systems.

A bottleneck: component availability

While fiber lasers share many of the basic features and challenges of conventional lasers, they also represent a substantial step up in manufacturing process requirements. First of all, the components used in fiber lasers, such as active and passive fiber, FBGs, high brightness fiber coupled pump diodes, power combiners (both for diode pumps as well as the output of individual fiber laser sources) all require highly advanced manufacturing technologies with capital intensive fabrication facilities running with high fixed costs. Fiber manufacturing in itself is a complicated process, and the fibers required in high power fiber lasers represent the pinnacle of fiber technology in every aspect, from core composition and doping, glass cladding and glass works, to coating materials. Only a handful of companies have managed to bring reliable high power fibers to the market so far, and all of these companies have invested substantial time and resources to perfect their manufacturing process. To make matters even more challenging, the fiber industry is mined with patents that sometimes are overlapping, so fiber manufacturing companies have had to invest significant resources in their IP and licensing efforts. But fiber is not enough – high brightness fiber coupled pump diodes are also needed; here the challenge is to achieve high output power, excellent efficiency, and very high brightness (in some cases well over 10 W output from 105 µm fiber, and well over 30 W from 200 µm fiber). The investment required in an advanced wafer fab and a packaging facility for volume manufacturing of fiber coupled diode lasers is high, just like the investment required in a fiber manufacturing facility. In both cases the fixed running costs are also high. Moreover, getting a new facility up and running takes significant time, in practice several years. Regrettably the situation is no better when it comes to fiber components, such as the FBGs and power combiners. Of course all this has to be achieved while providing the market a product at very low EUR/W cost in order to make the fiber laser competitive in the market place. Premium pricing is not possible.

The advanced technology, high investments and high fixed costs have left the value chain quite scarcely populated, creating a bottleneck for the laser industry to adopt fiber laser technology. For a value chain to develop the components manufacturers need customers willing to spend money on fiber laser components. Unfortunately that market is still limited: current laser companies have been quite slow in adapting the technology, since fiber lasers cannibalize the sales of their existing products built on legacy technology into which these companies have invested previously. The only big fiber laser company, IPG, has chosen a fully vertically integrated strategy to secure supply and reduce cost. Thus fiber laser components manufacturers are left to scramble together their business from various sources; corporate advanced research, military and research projects, and other sources of development funding. Some of the companies have had to move forward in the value chain, from being a components supplier to becoming a complete laser supplier.

All in all, companies supplying fiber laser components are few in most parts of the value chain. While there is a reasonable choice of diode suppliers, the number of fiber, fiber component and fiber submodule suppliers is quite limited. Another bottleneck is the limited availability of good commercial grade design software for fiber lasers. Clearly this type of scarcely populated value chain makes it difficult for laser companies to adopt fiber laser technology – there simply are not enough suppliers available.

Industry dynamics – vertical integration?

Whether the value chain will be populated and whether current component suppliers can reach a reasonable size to be profitable, remains an interesting question. The chances are that some of the big laser companies will decide to buy up what is available to secure in-house supply of fibers, components and diodes (in fact, many – such as Coherent, Spectra-Physics, Rofin Sinar and Trumpf – already have diodes in-house, due the importance of diodes for DPSS). This would deplete the value chain further and new investment in the components value chain may be hard to find (the current companies were, as a rule, financed by the telecom boom, which is unlikely to repeat itself). The industry value chain dynamics will be interesting to watch over the next few years! Many predict that only companies employing a fully vertically integrated approach, such as IPG, can compete successfully.

Process parameters needed

While making a good fiber laser is a challenge, it is not the only one a laser company faces. Fiber lasers, in terms of their performance parameters (in particular high beam quality and high peak powers) are quite different from currently used lasers. This is a particular challenge in materials processing, where high process quality and stability requirements mean that processing parameters must be just right. In order to use fiber lasers customers need optimized processing parameters. New process approaches may be required and may require significant time and investment. For example, one of the interesting issues right now is whether randomly polarized fiber lasers can effectively be applied to thick material cutting – it seems the jury is still out on this issue. Creating a multi kW linearly polarized fiber laser is a major challenge even for industry leader IPG, so a process parameter solution would be much preferred.
The importance of the Fraunhofer institutes, TWI, universities and public application laboratories around the world that develop process knowledge cannot be overstated – much good work has been done by these early adopters and researchers over the past years and much more will be needed.

Time to act!

There seems to be plenty of challenges, some still unaddressed. However, companies who have brought fiber lasers to the market, led by IPG and followed by many others, have each in their own way managed to tackle these challenges. It can be done! Thus this article seeks to encourage others to follow. Fiber lasers provide significant benefits and are attractive for many markets, but making good fiber lasers takes effort. Fiber laser technology is too important to be left to one big company alone, so the sooner some of the big incumbents in the business come out with their solutions, the better. In particular large laser companies in Europe should start moving, so that laser technology remains strong here.

Expect more excitement – industry dynamics and products

The impact of fiber lasers on the laser industry will be interesting to watch, whether one participates in the competition or is a customer.

INFO

It is all about the components!

There are several crucial components required to make a good fiber laser. Each component has specific challenges:

- **Pump diodes:** A sufficiently bright and powerful fiber coupled pump source is needed. This means high brightness diodes with high reliability, at a very low cost and in large volumes. Achieving good yield in production is crucial.
- **The active fiber:** To provide gain, a robust doped fiber that can handle the power (that is, does not suffer from photodarkening) is required. The active fiber must have very low losses and no imperfections that might cause scattering and reduce the beam quality. For pulsed applications it is important to reach high doping levels to reduce active fiber length and prevent nonlinearities. The fiber must also have very good splicing properties, for low loss connections to other fiber components.
- **Mirrors** for the cavity are made by FBGs that have to handle high power levels without optical degradation (in many cases the pump power goes through the FBG) and must have good splicing properties.
- **Pump Combiner:** The pump light is typically brought into the active fiber using power combiners, making it possible to use a large number of fiber coupled diodes for pumping. These combiners must be able to handle high levels of pump power, and must exhibit very low loss (losses cause heat, so any excess loss here spells trouble). Most pump combiners are made with a complicated and fairly non-scalable manufacturing process, so being able to make these components at a low cost and high volume is a tough challenge.
- **Isolators:** Good isolators are crucial for protection against back reflections especially for pulsed fiber lasers due to the extreme peak powers they produce (CW or modulated CW typically do not require isolators). Isolators may also be needed to protect the pump diodes from feedback due to intracavity pulses. Given that most pulsed fiber lasers use MOPA architecture, isolators often serve an important role in separating the gain stages from each other.
- **Output combiner:** For high power CW yet another type of combiner is needed, currently not readily available in the market. This combiner superimposes the power of several (typically about 400-800 W) fiber laser submodules to create kW-class output. Extremely low losses are absolutely crucial, as well as minimal degradation of the final output beam quality.
- **Power supply:** High power CW lasers are increasingly applied in "modulated" mode, which means they are rapidly switched on and off by modulating the pump diode current. While both diodes and the fiber can handle such modulation without difficulty, modulation puts significant stress on the current sources used to drive the diodes. Thus highly reliable current sources able to handle modulation are crucial.
- **Beam delivery:** Finally, to get the fiber laser output to the workpiece, passive transfer fiber (and cable) is needed, in addition to robust fiber connectors and beam switches. Low loss and beam quality preservation (or adaptation) are key.

FIGURE 5: **Quality control is essential during the whole fiber laser manufacturing process.**

The competitive dynamics induced by this new technology is very hard to predict, but certainly some very interesting scenarios are possible. For example, consider the possibility that IPG is able to keep and extend its position, pushing prices down so that new entrants, incumbents and component suppliers alike are suffocated. This would imply the appearance of the hardware equivalent of Microsoft, the "Microsoft of lasers". Microsoft is facing a challenge from Open Source Code consortia (like the Linux movement), but what would be the mechanism to challenge the "Microsoft of lasers"?!
While such scenarios may be a bit far fetched for industry analysts, it is clear that fiber laser technology brings new elements to the laser industry. The high investment and high fixed costs required to obtain the manufacturing capability of key components imply that companies must sell their products widely. Platform design and serving as many markets as possible are inescapable consequences. The need to run the expensive factories at capacity implies high volumes, so there will be a significant pressure on price all the time – fiber lasers lead to a volumes game, rather than a high margin game. For customers this is good news – you can expect more performance, lower cost, less maintenance and easier operation of the laser.

Expect more excitement – technology development continues!

Anyone who has participated in the major optics conferences over the past few years has certainly seen some amazing progress in the field. New results continue to come in steadily. Novel approaches for ultra-large mode area fibers that provide single mode output at ever increasing powers are only one part of the many interesting research areas. New fiber structures, fibers with integrated functionality and non-circular core fibers indicate that fiber laser companies can steadily offer more performance at a lower cost for years to come. Photonic crystal fibers open new application areas in medical and measurement, and high efficiency diodes provide further improvement of wall-plug efficiency. Coherent beam combining will open up exciting opportunities to create and control ultra high power laser beams.
Much of the research and development work is funded by military development funds, but the progress made will spill over to many commercial applications. Thus continued rapid technological advancement of fiber lasers seems like a sure bet. We can expect more and more integration, more power and better beam controllability. Increasingly monolithic solutions and sophisticated manufacturing processes will make it possible to reduce manufacturing cost and increase reliability, thus reducing total cost of ownership for customers further. All in all, fiber lasers and the underlying technologies will be crucial enablers in taking us to the "century of the photon".

Summary

Fiber lasers are a welcome addition to existing laser technologies and have some unique technological advantages. The promise of this technology can be seen in products that have been available for a few years, but there are still few large commercial suppliers of high power industrial grade fiber lasers, IPG being in practice the only one. This is likely to change in the next years, as existing large laser houses adapt this technology in their products. This can be expected, since fiber lasers do not only promise better performance, but also unprecedented opportunities for capturing economies of scale and extending market reach. The same underlying technology and components can be used across applications and markets, creating significant synergies in development and manufacturing. One of the interesting open questions is whether fiber lasers will be offered only by vertically integrated players, such as IPG, or whether a full component value chain can develop to challenge the vertically integrated model. Should the vertically integrated model win, an interesting follow-on question is whether IPG can extend its current lead to become the "Microsoft of lasers" or whether other players (conventional laser companies or players from the telecom market) can catch up to challenge IPG. An ability to successfully compete in multiple markets and to capture volume economies may be decisive, in addition to strong skills in partnering.
Looking at the latest developments both in the market place as well as scientific conferences, fiber laser technology is continuing its advancement and looks poised to become a key technology in most major laser application markets. We can expect the next five to ten years to continue with all the excitement and development that we have enjoyed so far!

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