Industrial Fiber Beam Delivery System for Ultrafast Lasers

New tools for laser machining applications

Max Funck and Björn Wedel

Free space beam delivery has long been the only option to transport high energy laser pulses. But what happens if the free space is surrounded by an optical fiber? Micro-structured hollow core fibers now make it possible to confine the laser light inside a small hollow core and transmit pico- and femtosecond pulses of high energy with excellent beam quality. Packaged into a rugged laser light cable, this is likely the start of a new era in laser beam delivery.

Ultrafast lasers exhibit a growing number of applications as they allow processing of practically any kind of material at unrivalled precision [1]. In order to get the optimum out of an ultrafast laser and establish the technology in industrial applications, exact control of the pulse in time, space and shape is required. A key component in a laser processing system is hence the optical interface between the laser source and the application: the beam delivery system. Its main purpose is to simply transport the laser beam as efficiently and undisturbed as possible from the laser source to the desired spot on the work piece.

However, additional functionality is increasingly demanded to enhance the laser beam in shaping it spatially and temporally. In the 1990s, the introduction of fiber based beam delivery systems for continuous wave (cw) diode- and solid state lasers has been a major breakthrough for the industrial laser application and are a de facto standard for cw applications up to multi kW laser power. Similar impact can be expected if a fiber beam delivery in ultrafast applications can be realized.

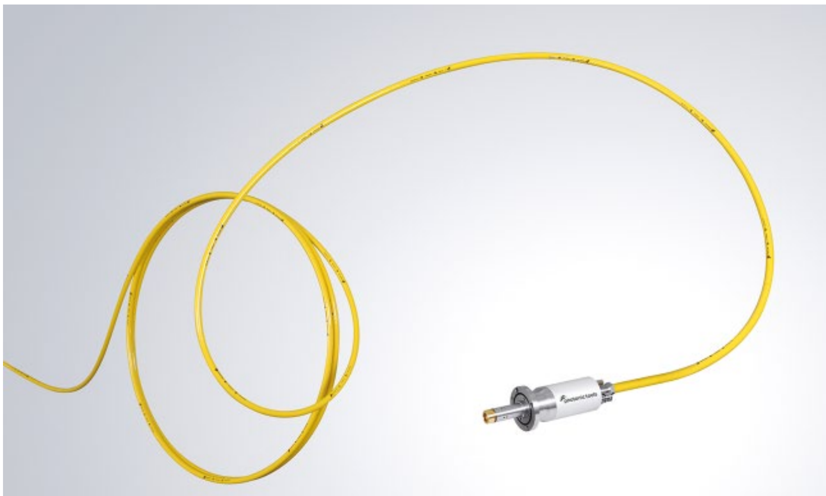

Fig. 1 Laser light cable for ultrafast applications

Beam delivery of ultrafast pulses

For the emerging class of ultrafast lasers with pulse durations below a few picoseconds and pulse energies high enough for material processing, free-space beam delivery is employed today. These mirror-based systems maintain the high beam quality of the laser source but can be very alignment sensitive (in particular for longer distances) and may suffer from contamination with dust and particles. They also introduce a large number of optical components into the beam path, which are potential sources of beam degradation. Additionally, a stable and well engineered support structure is required and typically the laser source has to be located in close proximity to the application. Typically, this involves a lot of cost and effort in the overall system design.

The lack of standardized beam delivery solutions further leads to individual solutions and hinders a wide application of ultrafast lasers in industrial applications. Adaptation of a new laser source requires additional alignment effort and finally significant cost. Fiber-based beam delivery systems cannot be found today, as classical fibers are no longer suitable. They suffer from dispersion making the pulses longer, exhibit insufficient damage threshold and for high energy pulses, nonlinear effects such as self-focusing, stimulated Brillouin scattering or Raman scattering take over and destroy the fiber material or the pulse profile [2]. As a consequence, ultrafast pulses for industrial applications cannot be transmitted using conventional glass fibers.

New fibers confine light in a hollow core

The limitations of conventional fibers can be overcome if it is possible to reduce the overlap between laser focus spot and fiber material during coupling. Micro-structured hollow-core fibers (MHCF) achieve just that (see Fig. 2), featuring light propagation mostly inside a hollow core (e.g. in air), enabling high power handling and drastically reduced nonlinear effects. Such fibers are

an evolution of photonic crystal fibers, which have first been developed in the 1990s by Russell, Knight and Birks at Bath University, UK. Since then, other types of micro-structured fibers have been developed by researchers around the world and demonstrated their potential for high power ultrafast laser beam delivery.

The first types to be developed where photonic bandgap fibers. They have a core size comparable to step-index fibers (for single mode operation) and confine the light inside an irregularity of the crystal like structure: the core. Another type of fiber is based on anti-resonant walls around the core and works by suppressing the coupling of core and cladding modes [3]. In either case, the core region of a single mode fiber can be much larger as with step index fibers allowing even higher damage thresholds. For this class of fiber more than 99 % of the laser light can be guided inside the hollow core, improving greatly on maximum permissible laser pulse energy up to levels in the mJ regime [3], well beyond many material processing applications. With proper integration into an industrial beam delivery system, ultrafast laser pulses with multi 100 W and multi 100 µJ can be reliably transmitted with excellent beam quality. A beam delivery system making use of such kind of fibers greatly enhances industrial application by increasing robustness, separating laser source and application, distribution of laser energy to multiple workstations and robot based applications.

Unlike with classical step-index fibers, the attenuation of micro-structured fibers does not only depend on material absorption but on the fiber geometry. Typically, several windows of high transmission exist over the spectral range and it is possible to achieve single mode operation even at relatively large core sizes around 30 or 40 µm diameter. The introduction of negative curvature walls of the hollow core has further reduced the mode overlap far below 1 %. This has enabled reduced attenuation and higher damage thresholds and paved the way to high power beam delivery and low dispersion. Due to the low dispersion on the order of a few ps/km · nm hollow core fibers are particularly suitable for ultrashort pulses down to the femtosecond regime. For wavelengths around 1 µm attenuation values between 30 and 70 dB/km or approximately 1 % per meter are possible over a spectral range from 900 to 1100 nm.

From hollow-core fibers to ultrafast beam delivery systems

A fiber-based beam delivery system consists of a beam launching system (BLS), a laser light cable (LLK) with integrated fiber and a processing head (see Fig. 3). In order to match the output of the laser source to the fiber, a coupling unit – or BLS – is required to adapt the size of the beam exiting the laser source and focus it to exactly the required spot size at the fiber tip. This will maximize transmission efficiency and increase the beam quality exiting the fiber. A stable spot position with respect to the fiber tip is absolutely mandatory as otherwise the fiber will easily be damaged at high pulse energies. Positioning needs to be accurate to a fraction of the spot size, typically in the micron regime, putting a high demand on mechanical interfaces and stability. The optical system is diffraction limited and (depending on the laser beam quality of the source) delivers a Gaussian intensity distribution at the focal position. Optimal coupling is maintained by dedicated alignment of the focal spot to the fiber core.

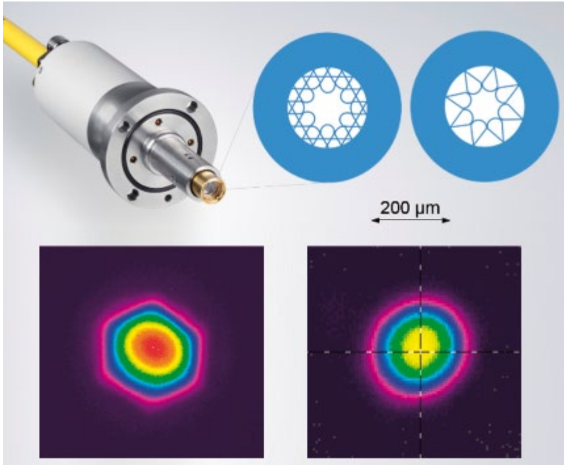

Fig. 2 Different types of micro-structured hollow-core fibers (MHCF) and their characteristic mode profile showing high beam quality (M^2 ~ 1.3)

The optical fiber itself is well protected from the environment. A rugged outer conduit, designed to withstand millions of bendings in robot or gantry applications, secures reliable operation in daily industrial use. Mechanical stress needs to be kept to a minimum even under rough operation and particles, dust or moisture should not enter the fiber as these will reduce the performance and may cause fiber damage. The connector design hence features a window, separated from the fiber end, to create a sealed environment and be far enough away to minimize laser damage to the coatings and bulk material of the window (see Fig. 3). The enclosed volume can be filled with clean air, or any other gas and may be pressurized or vacuumed. The fiber itself is mechanically held into position with good thermal contact. Water cooling is optional to reduce thermal effects at higher power levels. A dedicated alignment of the fiber tip with respect to the connector interfaces guarantees high repeatability when changing laser light cables. Reconnecting the same cable requires virtually no realignment of the laser fo-

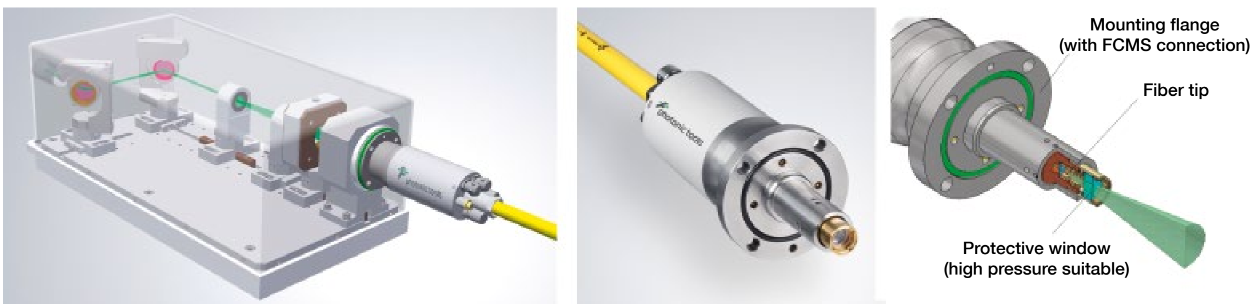

Fig. 3 Beam launching system (BLS) to connect laser source and laser light cable together with laser light cable connector for ultrafast laser applications.

cus. With the given connector design, different kinds of fibers (different core sizes) can be easily adapted. A flange type mounting supports high precision interfaces and is quickly connected, at the same time the o-ring seal offers a safe protection while used in typical industrial manufacturing conditions. In addition to the optical functionality, the laser light cable can feature security functions known from high power laser light cables. The protective conduit will protect from exiting laser light in case of fiber breakage. Also, fiber break (FCMS) and proper connection of cable and coupling unit are monitored according to industry standards.

Application to industrial ultrafast lasers

Performance evaluation of the fiber beam delivery with industrial ultrafast laser systems ranging from 3 to 200 W average power, 300 fs to 10 ps and pulse energies between 3 and 250 µJ reveals the full potential of the new technology. With proper coupling using a dedicated beam launching system, the laser light cable can operate over a very wide range of ultrafast laser parameters. Pulse durations down in the femtosecond regime can be transmitted as well as average powers of multi 100 W and pulse energies of multi 100 µJ with typical transmission above 90 % for a 3 to 5 m long cable. Coupling efficiency is constant even for different power levels, indicating very little focus shift with respect to the fiber end face and enable applications with fast power modulation. Physical limitations are only reached for high pulse energies that can damage the fiber end face, overheating due to fiber losses at high average powers and pulse degradation due to nonlinear effects at high peak powers. With optional water cooling and evacuation of the laser light cable connector very high average powers and high peak powers can be handled as is illustrated in Fig. 4 with experimental values from field testing.

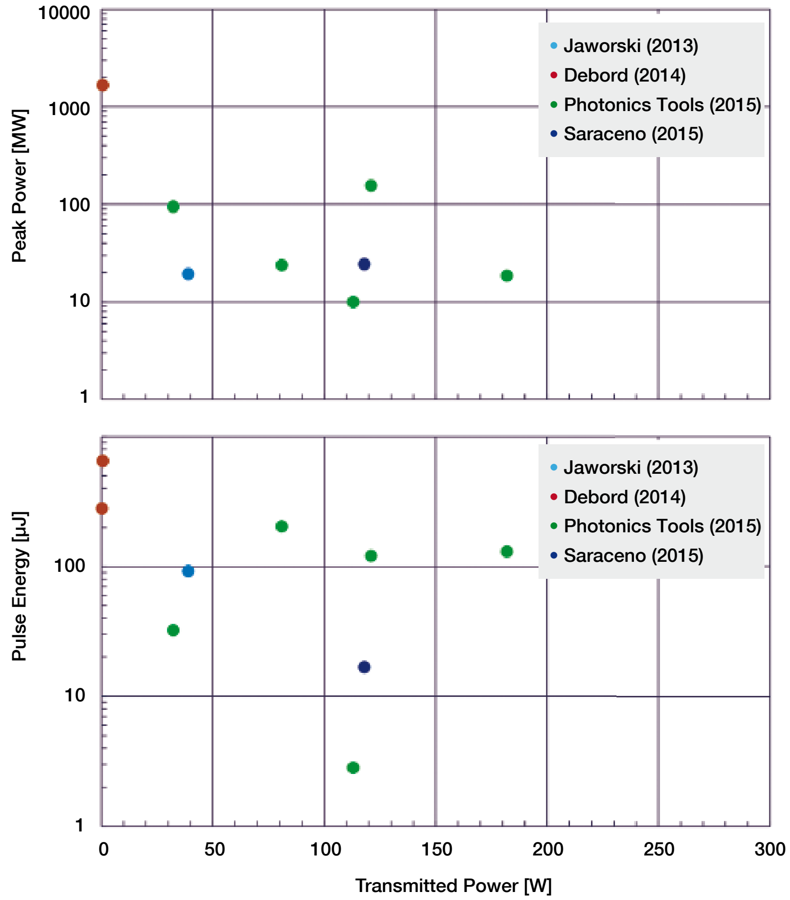

Fig. 4 Results from field evaluation and comparison to selected values from the literature [4, 5] demonstrating high power and high pulse energy performance of fiber beam delivery

Generally, the damage threshold is greatly influenced by the coupling losses and hence by the quality of the beam launching conditions. The experimentally obtained results are derived from representative field testing with standard ultrafast lasers and beam quality values M^2 between 1.1 and 1.3. Given a proper alignment, the delivered beam quality at the output of the laser light cable is also very high. An M^2 of 1.3 is generally achieved. Fig. 3 shows the according near field images for two different kinds of hollow core fibers with characteristic polygon shapes in one case and a more symmetric near field in the other. Both have an M^2 of 1.3 and very symmetric far field profiles. For short pulses with high peak power (e.g. > 30…50 MW), nonlinear effects in air start to play a dominant role and evacuation of the laser light cable connector is recommended in order to reduce spectral broadening of the pulse and optimize the beam quality of the transmission.

Hollow core fibers are generally known for being sensitive to bending. If the fiber is bend to a too small radius, attenuation increases and the beam quality can suffer. In addition, near and far field distributions after the fiber can be affected. Changing the bending radius to 20 cm and even moving and shaking the cable causes changes in the transmission on the order of only 1% and are hardly measurable. The rigidity of the cable prevents stronger bendings in most practical situations. The beam profile shows dislocations of the intensity pattern which are a fraction of the spot diameter and depend on the choice of fiber. Typically, dislocations are less than 3 to 5 % of the spot size sufficient for high precision machining.

Company

PT Photonic Tools GmbH

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Photonic Tools' products are tailored to address the interface between laser source and application. With a clear focus on increasing the productivity of industrial laser processes Photonic Tools provides state of the art beam delivery solutions, processing heads, system modules and components as well as engineering support and consultancy. The company currently employs 16 people and has been founded in 2013 by Dr. Bernhard Lummer und Dr. Björn Wedel.

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Depending on the choice of fiber, the properties can be tailored for specific applications. Beam quality and robustness against dynamic changes of the laser light critically depend on the fiber structure as do transmission and damage threshold.

In addition to mere beam transport, hollow-core fiber technology offers new degrees of freedom to tailor the pulses. Through deliberate control of nonlinear effects, it is for example possible to achieve pulse compression. Here, self-phase modulation of the laser pulse is induced inside the fiber. By controlling the gas pressure inside the laser light cable connector, the resulting spectral broadening and induced pulse chirp can be accurately adjusted and pulses compressed with an external compressor. It is thus possible to alter the pulse duration over a very wide range of pulse parameters. Compression factors of 3 to 10 are typically possible such that a 1 ps pulse can be compressed to a few 100 fs.

Conclusion

Fiber-based beam delivery systems have once paved the way for industrial application of diode and solid state lasers in material processing. For ultrafast lasers, similar solutions are now available and have the potential to similarly impact the ultrafast laser applications. The biggest advantage will be a far simpler system integration facilitated by the laser light cable: enabling the laser to be dislocated from the application and the movement of the processing machine, there will not be a need for a heavy support structure and a delicate free space beam delivery system. A simpler exchange and service of components is an additional benefit. These technical advantages go along with major reduction of the total cost of ownership for the overall laser system installation.

Application results show that excellent beam quality, pulse duration and power of a laser can be preserved over distances of several meters of fiber, integrated in a beam delivery system. Both transmission and beam quality are robust to mechanical loads thanks to a rugged design of interfaces. Bending and movement of the laser light cables within typical limits of bending diameters do not change power transmission and only have a small effect on the location of the intensity profile. For ultrafast laser applications between 900 and 1100 nm wavelength, a laser light cable can easily transmit hundreds of Watts average power and hundreds of µJ pulse energy.

DOI: 10.1002/latj.201500030

[1] *K. Sugioka* and *Y. Cheng*: Light: Science & Applications **3** (2014) e149

[2] *A. V. Smith* et al.: IEEE Journal of selected topics in quantum electronics **15** (2009) 153-158

[3] *Y. Wang* et al.: High Power Laser Science and Engineering (2014) 17-28

[4] *P. Jaworski* et al.: Optics Express **21** (2013) 4986-4994

[5] *B. Debord* et al.: Optics Express **22** (2014) 1118-1121

Authors

Björn Wedel studied physics at Berlin Technical University and earned his PhD in 1994 from the Optical Institute of Berlin Technical University while working as a project engineer at INPRO. From 1994 to 1997, he was senior engineer and project manager at Lumonics Ltd. in Rugby, England, before founding HIGHYAG Lasertechnologie GmbH which he managed as CEO until June 2013. In October 2013, he founded Photonic Tools GmbH together with the former CFO and co-founder of HIGHYAG, Dr. Bernhard Lummer.

Max Funck studied mechanical engineering and received his B.E. from Dartmouth College and Master and PhD from Aachen University, conducting research on optical design, tolerancing as well as on the assembly of lasers and optical systems. In 2012, he joined Carl Zeiss' corporate research center working on digital microscopy systems. Since 2014, he is head of research and development at PT Photonic Tools focusing on the development of enabling technologies for ultrafast laser applications.

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