SELECTIVE REMOVAL OF CONFORMAL COATINGS BY PULSED ULTRAVIOLET LASERS

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ABSTRACT
Within the microelectronics and medical device industries, thin conformal Parylene coatings are deposited on sensitive components in order to offer protection from, and biocompatibility within, a wide variety of environments. Oftentimes these coatings need to be removed from select areas to provide access to underlying circuit components. As electronic devices continue to miniaturize any conformal coating removal solution needs to provide even finer cut resolutions, all while not compromising quality, cost, and throughput demands. Pulsed ultraviolet (UV) laser machining offers a high-precision, high-throughput solution with no compromise on quality.

Key words: Parylene, conformal coating removal, ultraviolet fiber laser

INTRODUCTION
Within the microelectronics device industry, thin (3 μm - 30 μm) conformal polymer coatings provide electrical, mechanical, and chemical protection from adverse environments. They also offer biocompatibility and biostability for implantable and non-implantable medical devices (e.g., printed circuit boards (PCBs), medical probes, and surgical instruments). Parylene (i.e., poly-para-xylylene N, C, D, etc.) is the most commonly used conformal coating for electronic devices due its attractive properties including high electrical insulation and dielectric strength, low vapor transmission to humidity and moisture, low permeability to gases, low defect density, transparency and chemical inertness. Due to its biocompatibility and biostability characteristics as well as chemical inertness, non-toxicity and ability to withstand various sterilization methods (e.g., autoclave and gamma radiation), the Parylene coatings are used for encapsulation of medical implanted devices to protect the active electronics from the physiological environments.

Vapor deposition polymerization (VDP) provides the most conforming, pin-hole free coat of Parylene over an entire device surface. In this process Parylene dimers are first sublimated then pyrolyzed into monomers, which are then cooled as they are introduced into a vacuum chamber where they condense, polymerize and conform over the entire circuit board or device. VDP coats the entire device with Parylene, but some areas, such as contact pads on a PCB, may need to be accessed after the coating process. In addition, since many specialty electronic devices are costly, repairing malfunctioning electrical components is considered a feasible option over device disposal. In both cases, Parylene needs to be removed cleanly and selectively, so not to damage underlying components. A common Parylene removal method is to mask select areas with adhesive prior to VDP and then peel afterwards. This method leaves irregular edges and often lets Parylene seep under the adhesive edges during VDP. Mechanical scraping is often considered a method of last resort since damaging the underlying components is likely. Micro-abrasion is a more precise method, but an abrasive needs to be chosen that does not damage underlying components and does not incur electrostatic discharge (ESD). There would also be a trade-off between quality and throughput as removal rate typically decreases with particulate size. For all of these methods, scaling production to higher throughput is labor intensive, costly, and difficult to implement, where consistent, reproducible part quality may be dramatically compromised. As electronic devices continue to miniaturize, some of these methods may not even offer a realistic solution given the repeatable, micron-level resolution required.

UV laser micromachining provides a Parylene removal solution with high yield and high throughput that meets these demanding precision requirements. Parylene removal is high quality, easily controlled, and deterministic. Throughput can be scaled higher often without making any large compromises on part quality. Laser micromachining workstations are fairly modular, allowing for different types of fixtures, optics, lasers, automation and processing methods to be readily installed.

Next we discuss the laser machining mechanisms of Parylene in the UV, what types of lasers are available in the UV range, what are the typical machining strategies and why one might select a particular laser type. Practical examples of Parylene removal are shown, and finally laser workstation requirements for high quality high speed Parylene removal are discussed.

UV LASER REMOVAL OF PARYLENE
In laser machining the amount and quality of material removal is dependent upon the target material properties

(e.g., optical absorption coefficient, heat capacity, thermal diffusion), the incident laser parameters (e.g., fluence, repetition rate, wavelength, power, pulse duration), and the processing conditions (e.g., process gas, debris removal).

Material removal typically relies on laser ablation, a mechanism that depends on light being absorbed within the bulk material leading to localized removal. Two general types of laser ablation mechanisms are photoablative and photothermal. In photoablation, or photochemical decomposition, the energy of incident laser photons is high enough that single photons couple strongly and directly break the chemical bonds of the target material. This can allow for a "cold ablation" removal process where little heat is transferred to the non-ablated bulk material. In photothermal ablation, the energy of incident photons is used to rapidly heat the target leading to vaporization. A collateral heat-affected zone (HAZ) may be minimized by choosing appropriate laser parameters for a given target material, for example by reducing the pulse duration to a few nanoseconds or shorter.

UV lasers operating at or below 266 nm are able to photoablate Parylene since many of the covalent chemical bonds found in Parylene both absorb strongly and break in this wavelength range (Figure 1). Photon energies at or above the bond dissociation energy of a chemical bond can break it. By using short ns pulse duration, photothermal ablation and HAZ effects are minimized, and pure photoablation is the dominant removal mechanism.

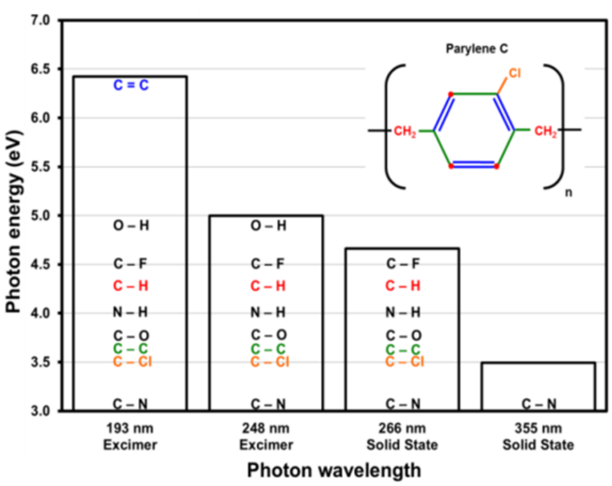


Figure 1. The photon energy for common UV lasers is shown. Included are several various chemical bonds found on polymers, which are placed alongside their bond dissociation energies.

Parylene removal rates when using 248 nm excimer lasers generally follow a logarithmic trend with laser fluence, agreeing with Lambert-Beer's law for optical absorption (Figure 2). The high optical absorption leads to precise removal per pulse and low ablation threshold fluence around 0.1 J/cm^2. The threshold for damage (e.g, melting) on typical bulk (semi-infinite) metallic substrates is above ~0.7 J/cm^2, which allows for a wide processing window where Parylene can be selectively removed from these substrates with high quality. Typically the fluence used is in the range 0.4-0.6 J/cm^2 to maximize the removal rate of Parylene without impacting the substrate. Ceramics such as alumina, AlN and zirconia have damage thresholds that are typically higher above 5 J/cm^2 and therefore ablation of Parylene coatings from such substrates can also be done with high quality with fluences up to 1 J/cm^2.

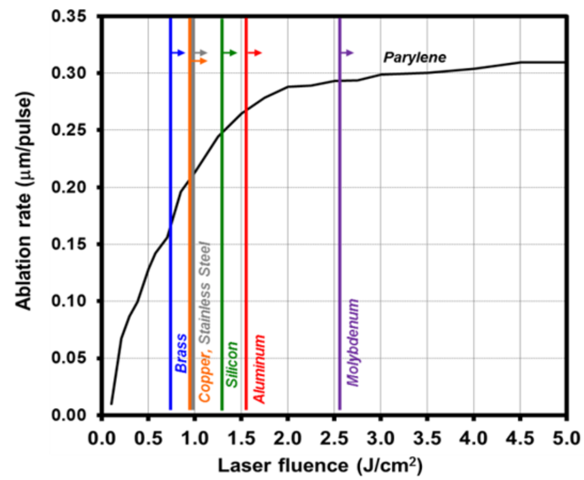


Figure 2. Ablation rate of Parylene vs. laser fluence (λ=248 nm). The damage thresholds for various bulk (semi-infinite) substrate materials are also shown.

For longer UV wavelengths such as 355 nm, photons cannot break as many chemical bonds since the photon's energy is inversely proportional to its wavelength. Consequently coupling of single photons into Paryelene is not as strong leading to longer linear optical penetration depth. Thermal controlled ablation can become predominant unless short pulses are used. If the pulse duration is short enough the high peak intensity can lead to nonlinear multiphoton absorption, resulting in strong optical coupling with Parylene regardless of the wavelength used.

At 355 nm and when using a short pulse duration of ~1 ns the removal mechanism becomes highly dependent on the energy density used, offering unique machining approaches. At low fluence between 0.2 and 0.5 J/cm^2 laser radiation can transmit through a thin layer of Parylene with little absorption, and can then couple with an underlying material such as a very thin adhesion promoter on top of the metallic or ceramic carrier, leading to its ablation. This creates a localized shock wave that can mechanically exfoliate the Parylene film above in a laser lift off machining process with little to no affectation to the bulk substrate (Figure 3). Coupling in Parylene increases above 0.5 J/cm^2 leading to an ablation driven removal process above 0.7 J/cm^2. At 1 ns the pulse duration is short enough that effective nonlinear multiphoton absorption can lead to adequate machining quality while minimizing thermal affectation of the Parylene and the underlying substrate. Longer pulses at 355 nm will tend to enhance thermal effects which typically leads to lower machining quality.

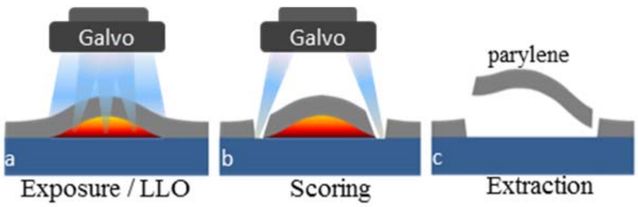


Figure 3. Schematic representation of laser lift off of Parylene when using short 1 ns pulse duration at 355 nm.

In the visible and near IR (i.e. 1064 nm) regimes standard nanosecond or longer lasers do not couple well with Parylene, and consequently are not typically a choice for laser machining of these coatings. Ultrashort lasers with ps and fs pulse duration can be used enhancing coupling due to high intensity multiphoton absorption and leading to high quality machining, but those are typically much more expensive than ns UV lasers, in particular fiber lasers.

CO_2 lasers operating in the far IR (i.e. 10.6 microns) can also be used to ablate Parylene, coupling reasonably well. However this is predominantly a thermal ablation process, often not leading to "cold ablation" such as that seen when using short pulsed ns UV lasers. Furthermore the much longer wavelength also impacts the minimum achievable spot size, and consequently these lasers are not an adequate choice if precise machining is needed with features below ~ 100 microns.

The discussion above highlights advantages and the flexibility of UV lasers when used for selective removal of Parylene coatings, with the optimum choice of laser wavelength and pulse duration a consequence of the particular application.

UV LASERS AND MACHINING TECHNIQUES

Two types of UV lasers typically used for Parylene removal are gas-based excimer lasers and solid-state lasers including fiber lasers.

The most common excimer lasers are Argon Fluoride (ArF, λ=193 nm, 6.4 eV) and Krypton Fluoride (KrF, λ=248 nm, 5 eV). These lasers have relatively short pulse durations (typ. 10-30 ns FWHM). The transverse beam profile of an excimer laser is quasi-Gaussian across its short axis, while its long axis has roughly a flat top intensity profile. The excimer beam is used to illuminate a mask, which is imaged and demagnified onto the target using an objective lens. If a very uniform fluence distribution is needed on target beam homogenization techniques (e.g., multi-element fly's-eye optics) can be employed. The demagnification (typ. 3× to 25×) is governed by geometrical optics and depends upon the objective's focal length and its distance from the mask. Bulk metal and thin-films (metal) on quartz are used as masks, which can have any shape, for example matching a pattern that needs to be removed from a target part. A step and repeat process can be used to machine repeat patterns and larger areas can be patterned by moving the part under the beam. Increasing throughput for higher-volume processes is often accomplished by using a higher average laser power. Single shot large area exposure (e.g., > 3000 μm × 3000 μm) requires an excimer laser with high pulse energy between 200 mJ and 1 J, which typically runs with repetition rates between 600 and 50 Hz, respectively, and average powers exceeding 50 W. A new generation of "low pulse energy" excimer lasers (< 20 mJ/pulse) are typically used for small area exposure (e.g., <1000 μm × 1000 μm) and run at repetition rates typically between 500 Hz and 1 kHz with average powers between 5 W and 15 W. These lasers provide long fill lifetimes, in excess of 80 million shots per fill, with laser optics lifetime in excess of 500 million shots, combining reduced capital and operating costs in particular vs. high pulse energy excimer lasers. KrF 248 nm excimer lasers typically lead to better fill and optics lifetime than ArF 193 nm lasers, and don't require purged beam deliveries, so they are often the preferred excimer wavelength for removal of Parylene.

Solid-state lasers such as bulk rod-type diode pumped lasers and fiber lasers generate laser emission typically in the near-infrared. Crystals with nonlinear properties are employed to either triple (~355 nm) or quadruple (~266 nm) the frequency of the primary harmonic. The transverse beam profile from these lasers is typically Gaussian, but can be shaped as needed. The laser beam is focused onto the target using simple far-field imaging techniques. Specific patterns are directly machined on the target by either moving the part, using motion stages, or by moving the beam, using high speed galvanometer or polygon scanners, or by moving both the part and the beam. Adequate energy density/intensity, overlap and beam size on target are critical for optimum processing conditions.

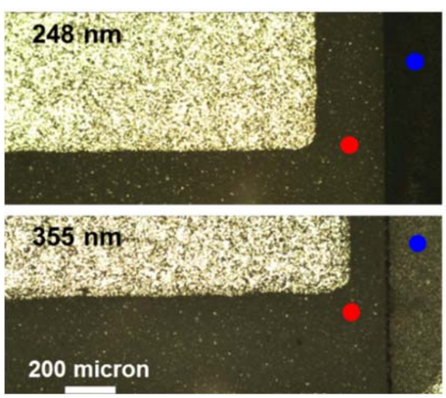
Typical UV bulk solid state and fiber lasers have pulse energies up to 1 mJ/pulse, repetition rates ranging from 1 kHz to >600 kHz, and pulse durations below 100 ns. Lasers at 355 nm have higher average power than lasers at 266 nm laser, due to losses in frequency conversion to the lower wavelength. However it is always necessary to adjust the wavelength to the application, defining which one allows for the best compromise of quality and throughput. While low pulse energy limits the target beam size (typ. <100 μm) vs. excimer lasers, the very high repetition rates possible can drive high laser power, and allow for high throughputs.

A new generation of IPG Photonics 355 nm pulsed fiber lasers was recently introduced. The IPG Photonics ULPN-355 series provides scalable average output power up to 30 W and constant pulse duration of 1.5 ns, with pulse energy above 50 μJ, and repetition rates up to 600 kHz. Being a fiber laser the ULPN is much more energy efficient and compact than other conventional solid state lasers, and provides a robust maintenance free design at a lower cost.

The choice of laser depends on the specific requirements of the applications. If a large area is to be machined with fine features, then potentially an excimer may be the laser of choice, since it allows for the shortest wavelength and highest optical resolution, with a large homogenous beam on target. That said excimer lasers require optics and gas replacement leading to high operating costs vs. solid state lasers in particular fiber lasers. On the other hand, if the application calls for machining of a number of different layouts then potentially raster scanning with a high repetition rate laser is the best choice, with easy conversion from a CAD layout to machined parts. Unlike rod type solid state lasers, fiber lasers allow adjustment of pulse energy and/or change of repetition rate without affecting any of the output beam parameters which means scalability with increasing average power is much easier to achieve.

EXAMPLES OF APPLICATIONS

Figure 4 shows the removal of a 15 microns thick Parylene film from a ceramic substrate using UV lasers at 248 nm and 355 nm. High quality was obtained for both cases using a fluence of 0.4 J/cm^2 at 248 nm, and 0.7 J/cm^2 at 355 nm. The excimer removal process required a final cleaning step at higher fluence of 0.7 J/cm^2 to remove debris accumulated during the machining step. Since the ceramic substrates have high damage thresholds they lead to great selectivity allowing for fluences up to 1 J/cm^2 to be used to remove Parylene with no impact on the substrate.



●Parylene not removed ● Parylene removed

Figure 4. Removal of Parylene C (15 microns thick) from a ceramic substrate using an excimer laser at 248 nm and an IPG fiber laser at 355 nm both showing high quality.

In a number of PCB applications the Parylene coatings are deposited onto thin film (< 1 micron thick) metal coated substrates. Excimer lasers operating at 248 nm (typ. 10-30 ns) will couple strongly with the Parylene leading to its removal. However, for adequate removal a fluence at or above 0.4 J/cm^2 needs to be used which can thermally impact the thin film leading to local melting or even vaporization. In such cases shorter pulse duration such as that provided by the 355 nm-ULPN fiber laser at 1.5 ns can be beneficial either by using a laser lift off removal mechanism or an ablative removal process depending on the fluence used.

Figure 5 shows the removal of an intact Parylene "disk" using a laser lift off mechanism with the ULPN fiber laser to detach the Parylene from the carrier substrate. A very low fluence around 0.2 J/cm^2 was used, enough to induce the detachment of the Parylene film (22 micron thick) without impacting the underlying very thin (0.5 microns) gold film. It is suggested that the thin adhesion promoter film deposited onto the gold layer prior to Parylene deposition is being ablated leading to local detachment of the Parylene film. A secondary laser "scoring" process was then performed using a higher fluence at 0.7 J/cm^2 to ablate a trench around the area of interest and allow for separation of the Parylene "disk".

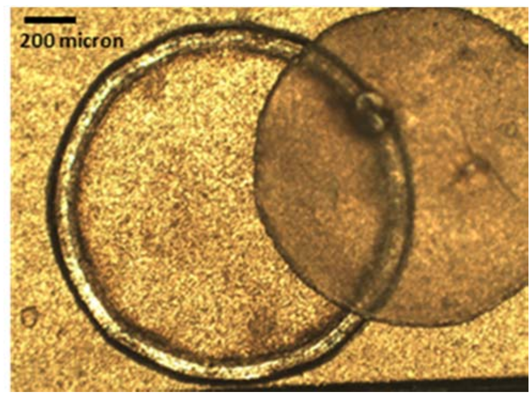
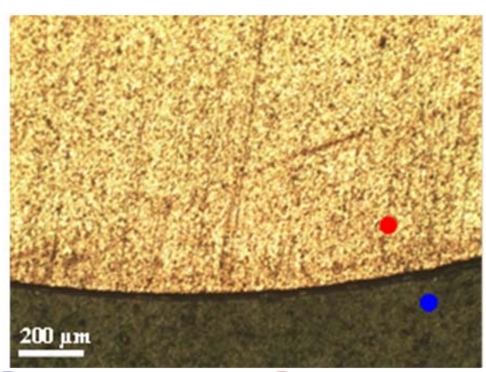


Figure 5. Removal of Parylene (22 microns thick) using a laser lift off mechanism to detach the conformal film, followed by an ablative "scoring" step both with a UV fiber laser.

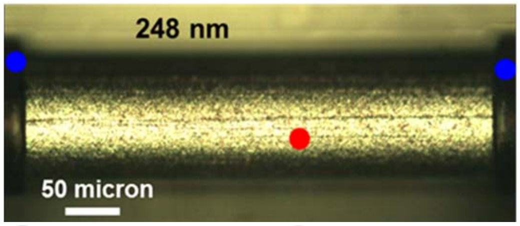
The shapes to be machined are easily defined using a CAD-CAM approach, and hatching techniques can be used to remove large areas by scanning the beam along various directions with adequate overlap to precisely remove defined areas. For example, consider a 6 microns thick coating. A typical removal rate of 0.1 microns/pulse requires ~ 60 shots/location for film removal. A 15 W 355 nm fiber laser with a repetition rate of 300 kHz and an on-target beam size of 35 microns diameter has a removal rate of ~4 mm^2/sec (Figure 6).



●Parylene not removed ● Parylene removed

Figure 6. Removal of 6 µm thick Parylene from a copper substrate using an IPG 355 nm fiber laser (~4 mm^2/sec).

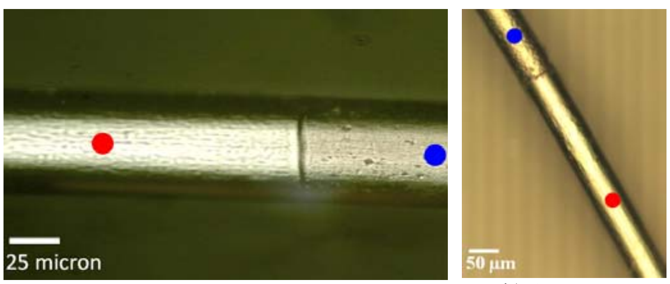
There are a number of applications where removal of Parylene from cylindrical substrates such as pins and wires is also needed. Figure 7 show 15 microns thick coating removed from a nitinol wire as used in medical device applications. The wire was rotated under the beam to ensure adequate removal from all areas of interest.



Parylene not removed Parylene removed

Figure 7. Parylene C (15 microns thick) removed from all sides of a nitinol wire using an excimer laser operating at 248 nm.

For probe card type applications small diameter metallic pins (Figure 8) are used for electrical contact and there is often the need to remove conformal Parylene from all sides of the pin including its tip. This can be achieved for example by directing multiple beams coming from several directions onto the pin.



a) 248 nm b) 355 nm

Parylene not removed Parylene removed

Figure 8. Parylene (3 microns thick) removed from metal alloy pin.

The process parameters need to be adjusted to ensure complete removal of the Parylene film. If using a laser lift off removal mechanism the entire film is detached, but if using an ablative removal mechanism some level of overpulsing is typically required to accommodate any process variations. This may lead to heat accumulation on the exposed parts especially pins and wires, where thermal dissipation into the bulk material is reduced vs. a flat semi-infinite substrate. A similar effect can happen for thin film coated parts with the thin film potentially accumulating heat faster than it can be diffused into the bulk material. For such parts it may be beneficial to use a machining strategy where a small laser spot is moved at high speed across the part as opposed to machining with a large spot simultaneously exposing the entire area to be machined. This is typically the machining approach used with the UV ULPN fiber laser, with its 1.5 ns also minimizing heat affectation when compared to excimer or standard bulk solid state lasers that have longer pulse durations.

LASER WORKSTATION

The prior results illustrate that process development establishes which laser and laser technique are better suited to meet manufacturing goals, thus allowing for specification of equipment options. In addition to machining quality requirements, including dimensional and positional specifications, considerations for high-volume manufacturing include throughput and cost of ownership. To address these requirements while allowing for machining complexity and versatility IPG Photonics offers a variety of workstations in which multiple laser types and beam delivery systems can be installed.

For mechanical and thermal stability the workstations feature a granite support structure to which the optical components and precision part handling stages are mounted. Fixturing largely depends upon the part geometry. While often custom tooling is needed, two-dimensional parts can be held using a vacuum chuck and then translated and rotated using multiple axes (e.g., X, Y, Z, θ). Three-dimensional parts (e.g., wires, pins) that require material removal on several sides can be held by a rotary lathe and rotated under the laser beam, or manipulated to ensure adequate material removal from all areas of interest which may require custom modifications to the beam delivery. Depending on the machining process, adequate debris removal strategies need to be considered. Process and high magnification alignment cameras are available, that can be configured to automatically align the part and beam(s) to micron precision using machine vision. Advanced features such as computer controlled illumination and automatic focus subsystems are also available. Integrated power and pulse energy monitoring allows the system to automatically check and adjust laser power and/or energy levels. The system can also check and correct for any drift in spot placement and variation in beam size over long production runs. The integrated software can easily convert CAD designs into macros that move the various motion axes in coordination with laser triggering, while also providing extensive data logging capabilities.

These workstations are available in manual load, semi-automatic configuration, or with optional Integrated Automation Platform cassette loaders, allowing for high-volume fully-automated manufacturing. Configurations with up to four cassette load/unload ports are available with a wide variety of integrated metrology and process control functions to ensure a highly robust production process.

CONCLUSIONS

Short pulse ns UV lasers can selectively remove conformal Parylene coatings with a dimensional precision that cannot be achieved using alternate techniques, while allowing for high throughput. When all system functions are considered (e.g., beam formation and delivery, vision alignment, part fixturing and movement and integrated metrology), a production tool can be delivered with the level of scalability and process traceability necessary when removing conformal coatings on today's most critical electronic and medical devices.

While the choice of laser depends on the exact application requirements a new generation of UV fiber lasers offers unique advantages vs. standard bulk solid state lasers. For example, constant pulse duration over the full range of pulse energy and repetition rate, which allows for very easy process scalability. The short 1.5 ns pulse duration of the ULPN fiber lasers at 355 nm allows for unique Parylene removal approaches. A laser lift off removal process is possible at low fluence (~ 0.2 J/cm^2), while higher fluences (≥ 0.7 J/cm^2) allow for ablative high quality removal. In addition these lasers maintain the typical advantages of fiber lasers such as compactness, high wall-plug efficiency, cost effectiveness, and robustness which makes them highly suitable for high volume manufacturing.