powerphotonic
enhancing beam performance

White Paper

Production of precision optics using laser micro-machining

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By Julian Hayes

Introduction

PowerPhotonic has developed a revolutionary new technology for the fabrication of freeform optical components in silica glass. This technology, based on laser direct-write micromachining, offers ground-breaking opportunities for the design, manufacture and supply of unique products that can transform the performance of a wide range of optical systems from acceptable to outstanding. This direct-write machining process allows optical surfaces to be made that are fully customised to a particular application, often enabling complex systems to realise diffraction-limited performance without extending the budget. The laser micromachining technology developed by PowerPhotonic has no symmetry restrictions, meaning whole new classes of optical surfaces can be created to fulfil requirements that were previously declared unfeasible. The only limit is your imagination!

The need for freeform

Conventional optical design is based on combinations of optics with planar surfaces, such as prisms and flat mirrors, and cylindrical and spherical surfaces, such as lenses and curved mirrors. Optical designers push performance far beyond that available by single plano and spherical elements in a number of ways:

- Spherical aberrations in high-NA systems are minimised by ingenious multiplet lens designs
- Crude beam shaping can be achieved by combining lenses in ways that exaggerate the effects of spherical aberration
- Multi-beam optical systems are fabricated by mechanically assembling arrays of large numbers of prisms and lenses

These approaches are taken to overcome the limitations imposed by conventional optical fabrication techniques (i.e. grinding and lapping flats, grinding and polishing spheres) but each incurs a significant cost, in terms of additional elements, mechanical assembly and the impact on system performance of an increased number of surfaces.

The availability of a process to generate entirely freeform optical surfaces would allow many serial (e.g. multiplet) and parallel (e.g. discrete lens array) optical systems to be reduced to a single, robust, monolithic, mechanical element. One of the best examples of this is the lens in a CD player read head: originally a heavy and expensive glass multiplet costing several hundred dollars, these are now small, light and fabricated in million-off quantities as plastic molded aspheres with unit price well below one dollar.

Three steps to freeform

Truly freeform fabrication offer a transformational change in the capability of refractive optics, overcoming the restrictions of conventional optics in three key ways:

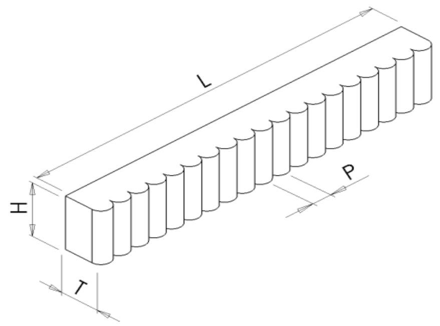
- Removal of shape restrictions
- Removal of symmetry restrictions

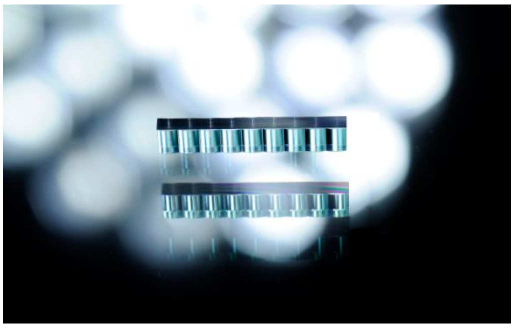
- Monolithic parallel integration of optical elements

Removal of shape restrictions, by moving from spheres to aspheres, enables improved system performance, along with reduced system cost and complexity. It also provides a new design flexibility that enables the creation of optical functions, such as Gaussian to flat-top beam transformers, that cannot effectively be fabricated using spherical surfaces

Removal of symmetry restrictions enables fabrication of astigmatic and anamorphic optics that are particularly important for asymmetric light sources such as diode lasers

Monolithic parallel integration of elements into prism and lens arrays avoids mechanical assembly costs, reduces adhesive-related issues such as cure time and outgassing and improves lens pitch tolerance, routinely achieving pitch error of well below 1µm.





Freeform application: Diode laser bar slow-axis collimator (SAC), a simple lens array

The gains available by using freeform optics extend well beyond these three key advantages, however.

Using a single surface, or a pair of surfaces in a single element, to combine multiple optical functions enables a reduction in system cost, weight, complexity, assembly time, whilst maximising optical performance and efficiency. A simple example of this is the PowerPhotonic SmileSAC, which is mechanically almost identical to a standard diode laser bar slow-axis collimator array, but incorporates the additional function of diode bar smile correction, increasing system performance with no increase in mechanical complexity or assembly time.

Freedom from the restrictions of standard fabrication techniques also enables greater freedom in the design tools that can be used – there is no need to adhere to standard asphere and acylinder descriptions: optical surfaces can be defined as generally as a point cloud or a nurb surface, providing the designer with unlimited scope for the realisation of new functions.

The simplest benefit of freeform optics is often the most powerful: freedom from the restrictions and compromises inherent in using the closest match of available catalogue components. When choice of lens radius of curvature is combined with conic constant and lens array pitch, stock lens arrays can only address a tiny fraction of the design space. Freeform provides the freedom to specify *exactly* what your design needs.

Freeform fabrication processes

The substantial benefits available from using freeform optics have driven the development of new freeform fabrication processes. And just as conventional optical systems are constrained by the capabilities of available fabrication processes, so are freeform optical systems. A number of different freeform optical fabrication techniques are available commercially, and each has its benefits and its limitations. Comparing their properties allows the most appropriate process to be chosen, based on application requirements.

This article is particularly concerned with glass micro-optics used in laser applications, though the processes described also have applications in imaging systems.

	Mechanical micro-machining (CNC-based grinding and Polishing)	**Precision glass molding**	**Grayscale lithography**	**Laser Micro-Machining**
Tool, Master, Mask	Grinding tools	Mold pre-form	Mask	None
Optic Substrate	Wafer or single optic substrate	Glass “gob”	Wafer	Wafer
Depth (Sag)	>>1mm	>1mm	<100µm	>200µm
Manufacturing Stability and Repeatability	Low, diamond cutting tool subject to wear	Moderate, mold subject to wear	Excellent	Excellent
Suitability for Freeform	Good for prototypes, poor for volume production	Poor	Excellent in volume, costly for prototypes	Excellent for both prototype and volume
Symmetry restrictions	Rotation or translation	None	None	None
Choice of material	Glass, crystalline	Specialist glasses	Glass, crystalline	Fused silica

Summary of freeform fabrication processes

Micro-grinding

Lenses can be produced by direct grinding and polishing using specialist machines. Although micro-machining and milling have been around for many decades, the advent of the cold war and subsequent defense spending has pushed the technology to a point where the capability to form complex micro-optics has become a practical reality for commercial applications.

Micro-grinding is widely used in the generation of rotationally-symmetric aspheres, and can be supplemented or replaced by the ultra-precision material removal of magneto-rheological finishing. It is now possible to create high precision aspheric lenses with high geometric accuracy (form error better than 100nm peak-to-valley) and low surface roughness (10 – 50 nm.)

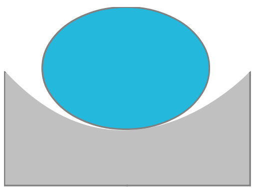
Micro-grinding is also widely used in the fabrication of parts with translational symmetry such as acylinder lenses and cylindrical lens arrays, both of which are widely used with high power diode laser bars and stacks.

Ultra precision machining using micro size diamond cutters can be used to create true 3D optics with relatively easy setup and fast turnaround. Micro milling and grinding technologies can be used for the production of plano, spherical, aspheric, conformal, and freeform optics. However, there are a myriad of wear mechanisms in micro-machining including stress related phenomena such as fracturing, abrasion, spalling, delamination, and thermally activated phenomena such as dissolution, diffusion, chemical reactions and adhesion, all of which hinder its use for volume applications.

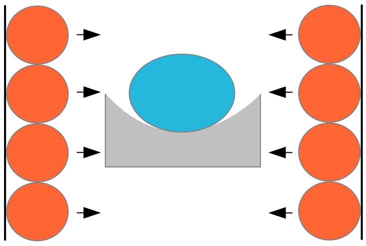
For complex micro-optic forms, micro-machining is generally not considered cost effective for mass production, and is typically used for one-off products. To be cost effective, precision machining is normally used to create a mold, which is then used to create the actual optic with molten glass.

Micro-Optic Precision Molding

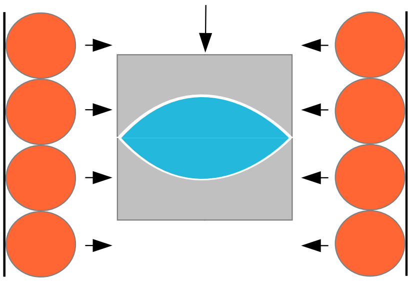
Precision molding is well suited to low cost and high reproducibility for large and medium quantities. The foundation of the technique is the micro-machining process described earlier. Heat and pressure are applied to a glass "gob" to create a shape in the form of the mold.



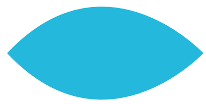
"Gob" of glass is placed in mold



Mold and glass "gob" heated up



Tool closed enclosing molten glass, molding glass "gob" to the required shape



Glass shape is removed from mold

Greyscale lithography

Lithography involves spin-coating a layer of photoresist over the surface of a glass or crystalline wafer (the substrate), patterning (exposing and developing) to produce a 3D structure in the resist, then etching to transfer the 3D structure into the substrate. Typical wafer dimensions for lithographic optics are 150-200mm diameter and 1mm thickness.

Patterning can be carried out using a number of different methods. Binary masking plus resist reflow allows the creation of a restricted set of lens arrays. True grayscale patterning, using either a grayscale mask or a direct-write (e.g. electron-beam) technique, allows the generation of arbitrary surface profiles, within process limits. Developing the resist involves hardening by baking then and wet chemical processing to remove exposed and hardened resist, leaving behind a layer with a patterned 3D structure.

The wafer is then exposed to a reactive plasma that etches the resist and substrate material at different rates, transferring the 3D shape patterned into the resist into a scaled version of this shape in the substrate, the scaling being determined by the selectivity of the resist. The most widely used etch processes allow sag up to a few tens of microns, while some specialist deep-etch processes can approach 100µm etch depth.

The main benefits of grayscale lithography are the flexibility in the range of freeform shapes it allows. Grayscale lithography is widely used to make arrays of spherical microlenses.

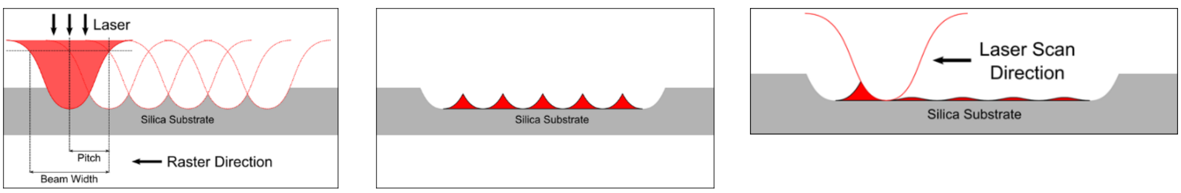
One of the main disadvantages of this approach is the high cost of first parts, driven largely by the cost of the grayscale mask.

Laser micro-machined freeform optics from PowerPhotonic

The cost and lead-time of first prototype parts is often seen as a significant barrier to the development of freeform optics: high NRE and long lead times prevent design iteration and force the adoption of conservative designs, restricting the opportunity to fully exploit the advantages that freeform optics can bring. Ideally, a freeform fabrication process would allow rapid prototyping at low cost and permit scaling to volume without having to re-engineer the product.

PowerPhotonic have developed a process that does precisely that. Our radically different technology delivers the game-changing performance advantages that freeform offers, along with the short prototype lead-time, low prototype cost and direct scaling to volume production required to enable new concepts in optical design to be implemented, verified and released as product in timescales and budget that would normally only permit catalogue components to be used.

PowerPhotonic's unique direct-write manufacturing process uses computer-controlled beams of laser light to machine 3-D refractive optical structures and to provide sub-nm surface smoothing. The result is the capacity to manufacture freeform structures with high optical performance, great design flexibility, rapid turn-around time and at low cost.



PowerPhotonic's laser micro-machining process

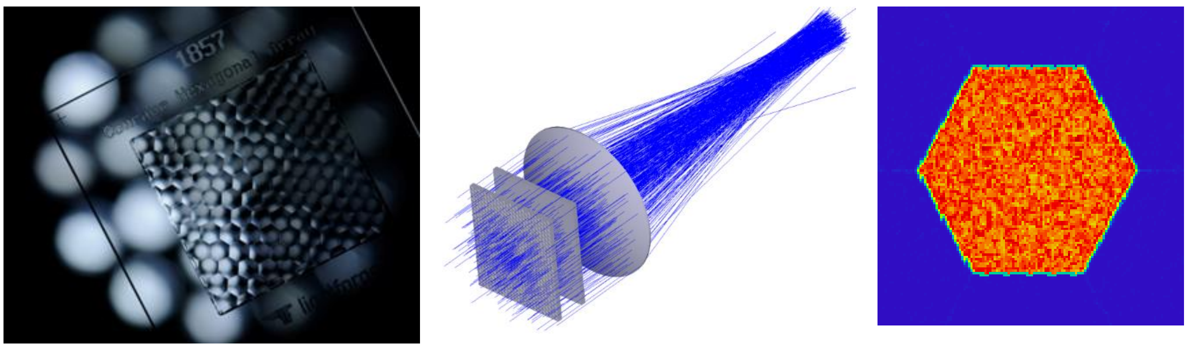
This process can generate smooth refractive surfaces in fused silica with sag up to 200µm. Since it is a fully direct-write process, wafer-scale processing can be used to generate high volumes of identical parts, and also high volumes of different parts, each individually serialized, tested, and traceable.

This brings the benefits of high-volume fabrication of freeform optics, without the prototype and low-volume price and lead time penalties of other approaches.

Freeform applications

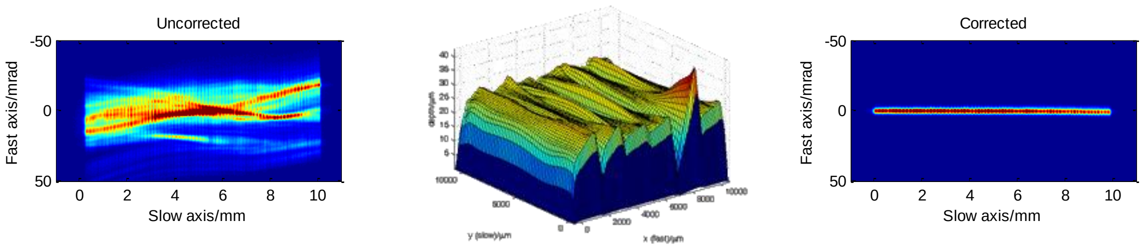
PowerPhotonic's freeform process can manufacture the types of optics typically manufactured by grinding, molding and lithography, such as diode laser slow-axis collimators and spherical lens arrays. In addition, the flexibility of this process make is straightforward to realise new designs that might otherwise remain untested due to the high NRE required for molded or lithographic prototypes, or the symmetry restrictions of the more cost-effective of the micro-grinding techniques.

Applications for PowerPhotonic freeform optics exploit the full range of flexibility offered by the process. Freedom of choice of radius of curvature, lens pitch and grid geometry enables the realisation of application-specific beam-shaping homogenisers, such as the hexagonal design shown.



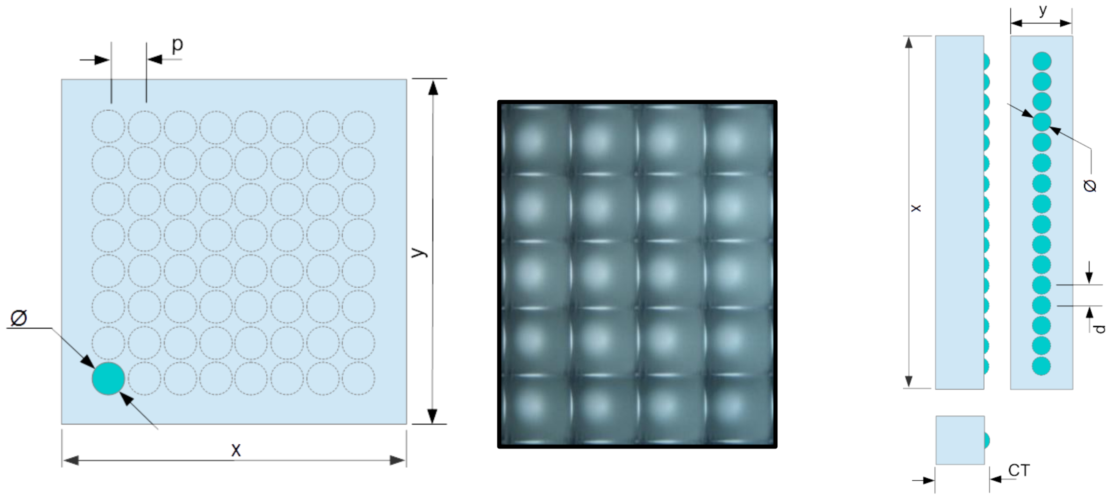
Freeform application: Hexagonal beam-shaping homogeniser

Absence of hard tooling or photomasks allows the creation of components where every fabricated part is different. This is exploited in our range of diode laser stack beam correctors, for which a fully-automated design and manufacture process runs from stack characterisation data all the way through to a finished, tested optic. Each of these parts is unique to its matching laser, and is traceable via a laser-written ID code, yet these parts are mass-manufactured and mass-tested as if they were identical components, with no engineering input required.



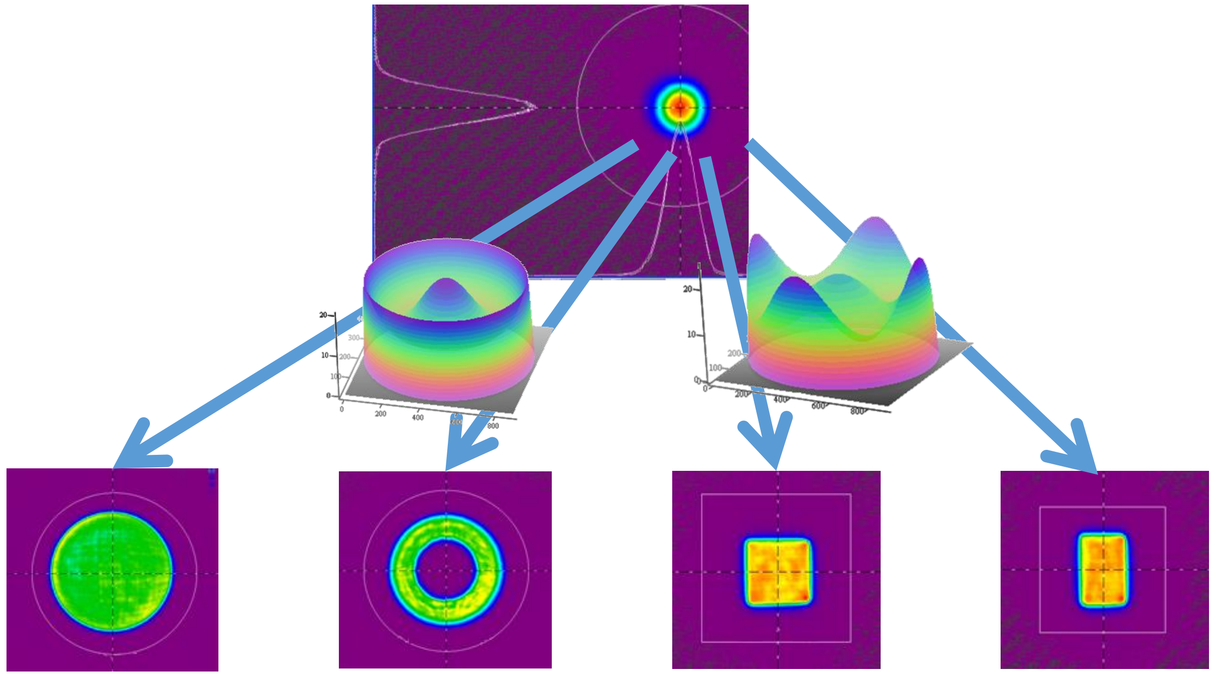
Freeform application: Diode laser stack beam correction

This fabrication process has the precision and accuracy to enable production of diffraction-limited optics, while the extremely smooth surface finish resulting from our laser polishing process avoids the scatter typically generated by mechanically-ground optical surfaces. Consequently, this process is ideal for making precision lens arrays for telecoms, where ROC and geometric accuracy are critical in achieving low insertion loss.



Freeform application: Telecom lens array

The absence of symmetry constraints makes it straightforward to fabricate and test a wide range of beamshaping optics that can transform a Gaussian beam into not only a circular flat-top, but also donut flat-top, a square flat-top, or a rectangular flat-top profile, each with a spot size tailored to your specific application.



Freeform application: Gaussian to Flat-Top beam shapers – top hat, no tails!

PowerPhotonic offers a full range of services for freeform fabrication, from build-to-print, when the customer already has a full design, through to design, fabrication and verification to the customer specification. All optics can be supplied with AR-coatings to customer requirements. HR coatings are also available, so the flexibility of freeform can be applied to reflective optics just as readily as it can to refractive optics.

LightForge™ rapid fabrication service

PowerPhotonic's ability to offer freeform optics to the mass market has been made one step easier with the unique LightForge™ rapid fabrication service. LightForge™ allows optical designers to create their own completely bespoke optical surface and have the fabricated part shipped in as a little as 2 weeks, for less than $3,000. LightForge™ gives optical designers the ability to create innovative new freeform surfaces, test new ideas and verify designs for production without incurring expensive upfront engineering charges and avoiding lengthy prototyping lead times. LightForge™ is used by our customers to create a wide range of refractive – and reflective - optical elements, from generic functions such as microlens arrays and beam transformers, to unique components such as diode laser smile correctors and wavefront compensator phaseplates, to completely custom freeform surface shapes. The scope of what can be done is limited only by the designer's imagination. The LightForge™™ fabrication service can be used both for one-off designs and for rapid prototyping as a precursor to volume production. Successful prototypes can then be directly scaled to volume using the same fabrication method.

The LightForge™ concept

LightForge™ was developed with customers in mind: many of our existing customers were experienced optical designers with the ability to fully design optical surfaces to meet their requirements, but found both the cost and the engineering effort required to translate their design into manufacture to be a significant barrier. The LightForge™ service acts as a standardised bridge between the customer's design and the fabrication system by:

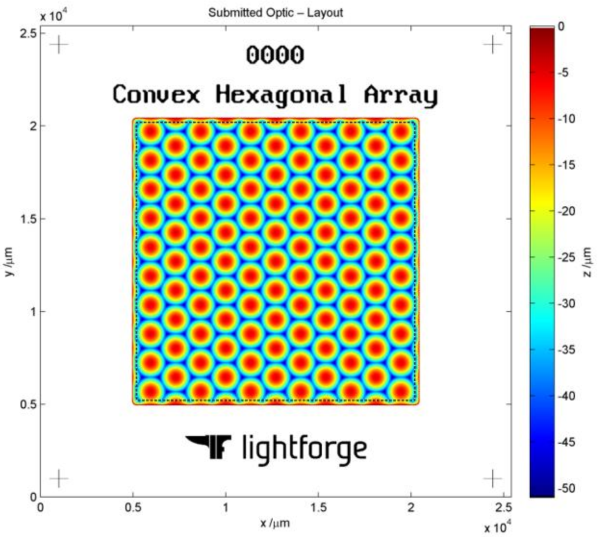
- Specifying a set of design rules and guidelines the optical designer should follow when creating an optical surface suitable for LightForge™

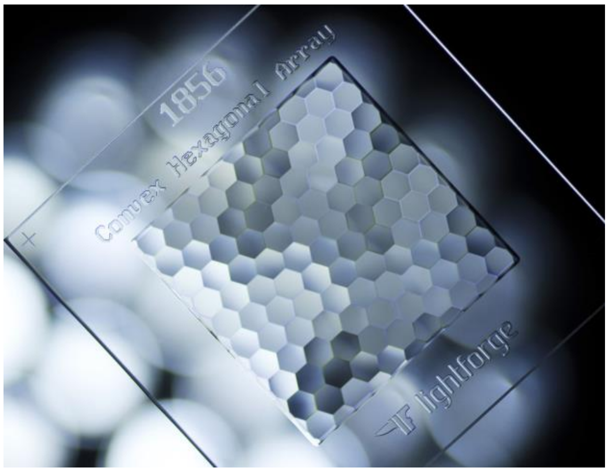
- Giving visual and numerical feedback on the optical surface during the LightForge™ submission process, and offering a range of solutions if the optical surface doesn't quite fit within the design rules
- Acting as a customer portal to the production process of their LightForge™ optic, with real-time updates of optic production status
- Creating a standard part layout that is fully communicated through the LightForge™ process, to ensure that what you see is what you get (WYSIWYG).

LightForge™ offers the optical designer a 15 x 15mm square area to fill in with whatever surface is required. That's 225mm^2 of completely customisable space for only $3000, an offering that is completely unique within the world of freeform micro-optics.

Submitting a LightForge™ surface

LightForge™ accepts surface shape data in a simple tabular data format that is easily generated in spreadsheet-type programs, or in computational packages such as matlab. The table specifies surface height *Z* on a square *XY* grid, and provides a precise specification of the entire optical surface over the clear aperture. This table is provided in a tab-delimited text file, called gridXYZ. The LightForge™ laser machining system directly uses this file to fabricate the optical structure, in compliance with the WYSIWYG philosophy. For customers who already have a design in ZEMAX, PowerPhotonic provide a ZEMAX macro that will automatically generate your valid gridXYZ file directly from a ZEMAX model. This means that even beginner optical engineers can start creating a huge range of optical structures with ZEMAX, safe in the knowledge that manufacturability is still an option. From astigmatic lenses to beamshapers to lens arrays, generating a custom freeform optic could not be simpler!





LightForge™ application: Hexagonal lens array

From Prototyping to Volume Production

LightForge™ is a powerful tool for prototyping a completely new optical design, but when the time comes to launch a prototyped design into a production environment how will it perform? Fortunately, LightForge™ uses exactly the same technology to manufacture optics as is used in PowerPhotonic's main volume production role, so there will be no difference between the prototype optic and the optic received in volume. The ability to use a prototype optical system as the direct basis for design of a production optical system can drastically reduce the cost to the customer of transferring from development to production. Indeed, because the LightForge™ optical area can be filled with whatever a customer requires, then diced out into smaller parts, a low volume production run of small optics can often be achieved using a single LightForge™ substrate!

Conclusion

Freeform optics can greatly simplify complex optical systems by minimising the number of optical surfaces and avoiding the need for mechanical assembly of large numbers of elements. The design freedom they permit enables a transformational improvement in performance and functionality when compared to conventional optics.

PowerPhotonic's freeform process takes this further, by making the prototyping of freeform optics fast and cost effective. This process scales directly from prototype to volume manufacture, providing a smooth path from design concept to product introduction, and ensuring that the manufacture of freeform optics remains consistent and cost-effective from early-stage development through to mature production.

The LightForge™ service takes this concept further still, and is a significant breakthrough in the world of custom micro-optics. It enables an optical designer to go from a design to real optic in as little as two weeks, all while being a fraction of the cost of other custom freeform optics solutions available on the market. This opens up a world of new possibilities for optical designers by who can now LightForge™ designs that were previously too expensive, time consuming or speculative to even attempt to prototype. LightForge™ makes freeform accessible, fast and affordable.