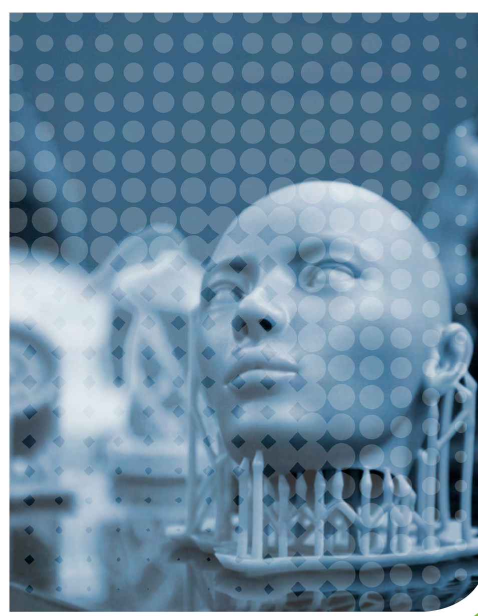
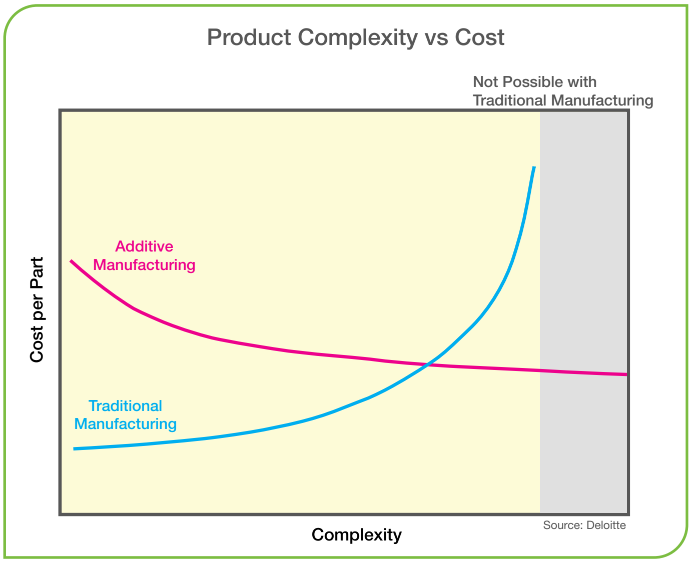
# TRANSFORMING VAT POLYMERIZATION ADDITIVE MANUFACTURING



# A FUTURE OF OFF-THE-SHELF CUSTOMIZATION

Often referred to as 3D printing, additive manufacturing (AM) is a revolutionary, disruptive approach to traditional industrial manufacturing. It is often thought of as a technique to make complex or lower volume products such as prototypes, concepts and custom one-off parts. But as product complexity increases, AM methods become less costly compared to traditional manufacturing (machining) methods. As such, AM is already used prevalently for production in several industries including aerospace, automotive, healthcare and energy. Demand for AM is predicted to increase further as software, computing power, materials and methods improve over time. In response, engineers will design considerably more products to be crafted specifically by AM methods, including products that are too sophisticated for traditional manufacturing to produce. In time, AM may be able to provide what today is thought of as a contradiction: off-the-shelf customization.




*As products become more complex, additive manufacturing becomes less costly than traditional manufacturing and, eventually, the only option.*

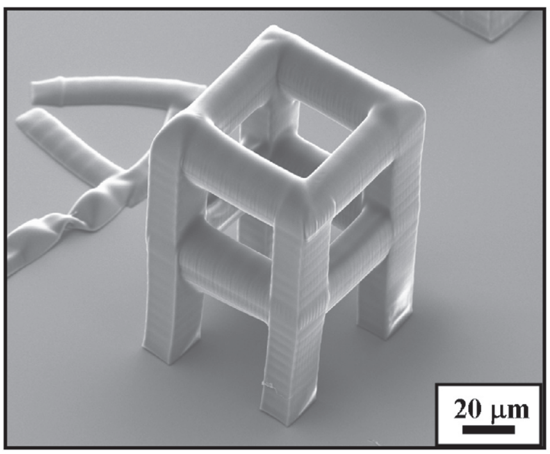
There are many types of AM techniques, and they all have in common the concept of adding or depositing layers of material to create a final object, as opposed to traditional subtractive manufacturing processes that remove material. One AM technique that has achieved commercial success, and is also recognized as the oldest technique, is vat photopolymerization (VPP), which is a liquid-based AM method that uses a light source to solidify a light-curable photopolymer resin to the desired shape, layer by layer. Some of the more popular types of VPP are stereolithography (SLA) and digital light processing (DLP).

VPP allows free-form structures to be quickly and easily produced. Additional benefits include high levels of accuracy and detail, smooth surface finish and relatively large build area capability. As VPP further progresses, it will play an important role in elevating the norm of current manufacturing.

## Vat Polymerization Challenges

Each type of AM technology has a specific set of benefits and challenges. One innate challenge of VPP is a relatively lengthy process time, much of which is due to time-consuming post-processing procedures after the objects have been created. Nevertheless, reducing the time of the photopolymerization step can meaningfully contribute to cutting the overall manufacturing time, and the type of light source chosen for photopolymerization—specifically for SLA, a laser—has a tremendous influence on the speed.

High accuracy and detail may already be benefits of VPP, but the quest to create parts with even tighter accuracy and finer details continues. This is especially true for two-photon polymerization (2PP), a technique based on the same principle of SLA, which can fabricate 3D microstructures suspended inside the liquid or gel without the need for a support structure. Such microstructures can be used in various applications—including biomedical, micro-electro-mechanical systems (MEMS) and microfluidics—and typically require nanometer-scale resolution. To meet such demanding requirements, 2PP systems must utilize ultrashort laser pulses to selectively cure polymer only at the laser's focal spot within the material.




*SEM image of a three-dimensional microstructure fabricated by 2PP*

Like all manufacturing processes, cost reduction is always a goal. AM is inherently expensive because it lacks the scale of traditional manufacturing and is often utilized for customized designs. And among the various AM technologies, VPP tends to be one of the more expensive processes. In spite of that, there are certain costs that can be controlled and even reduced. For example, components that make up an AM system, including lasers and optics, not only count towards the cost of the entire system, but they also impact how costly the manufacturing process itself will be as well as maintenance costs. This may only be a portion of overall cost, but it all adds up when trying to achieve off-the-shelf customization.

## The MKS Advantage for Vat Polymerization

MKS understands the challenges faced in designing and building VPP systems. We've turned this knowledge into unique product features that provide an advantage when used in VPP. Some of these features are described here.

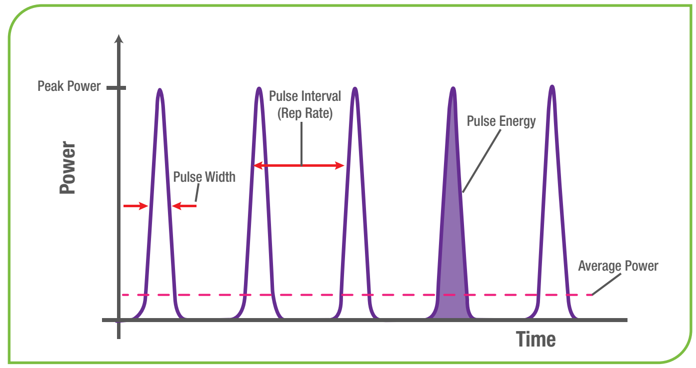



*Illustration of a Q-switched laser pulse train*

## Fast Q-Switched Lasers

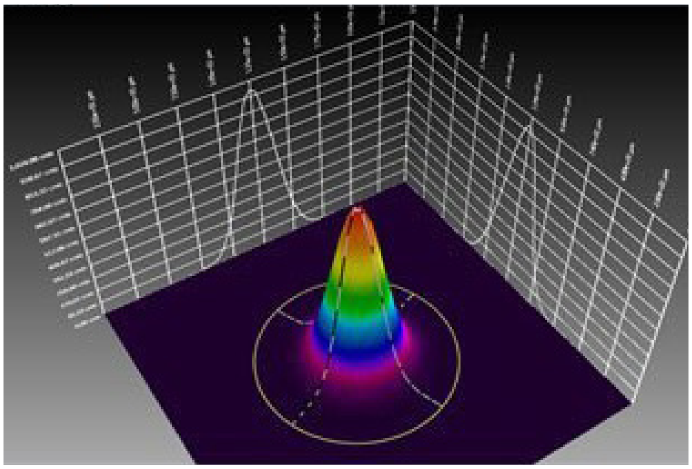
Q-switched lasers with output power ranging from hundreds of milliwatts to a few Watts, like the Spectra-Physics® Explorer® One™ series, are the superior and lower-cost choice compared to continuous wave (CW) lasers. Q-switched lasers dissipate a fraction of the heat compared to CW lasers, resulting in lower cost of ownership due to reduced cooling requirements.
As SLA is a scanner-based technology for creating very fine structures, the pulse repetition rate of a Q-switched laser should be at least in the tens of KHz. To scan even faster and reduce processing time, lasers with repetition rates of a few hundred KHz should be considered.

The rise time of a Q-switched laser is also important because the system jumps from vector to vector to cure the resin, so the laser power must rise from one pulse to the next very quickly. Explorer One lasers have demonstrated the ability to rise to approximately 90% of maximum power within one to two pulses.

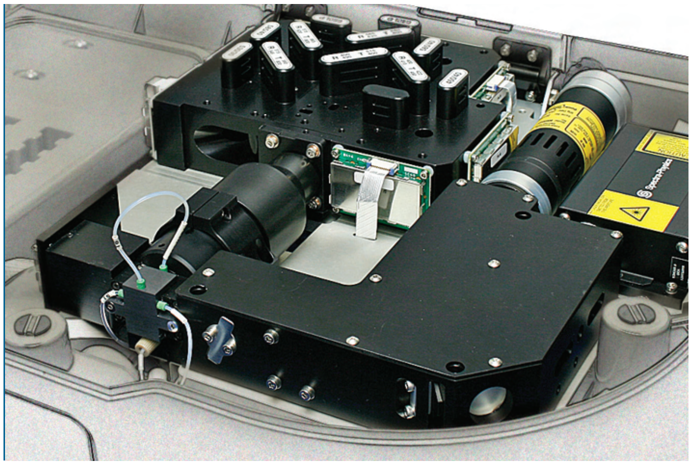
## High Accuracy UV Lasers

To consistently produce high resolution SLA parts, it follows that high accuracy lasers must be employed. UV lasers are the best, and essentially sole, option not only because of their curing properties with photopolymers but also because they are capable of delivering very fine beam spots at the curing point.

In addition to the size of the beam diameter, the quality of the laser beam critically affects resolution. A good measure of beam quality is $M^2$, or how much it diverges from an ideal Gaussian beam. Lasers with $M^2$ as close to one (i.e., as close to an ideal Gaussian beam) will produce higher resolution components.



*Measuring $M^2$ of a Gaussian beam*



*Integrated assembly with optics, opto-mechanical components and motorized positioning.*

Here again, Explorer One UV lasers offer outstanding performance with close to ideal Gaussian beams ($M^2 < 1.3$) and beam diameters at the waist going down to less than a millimeter.

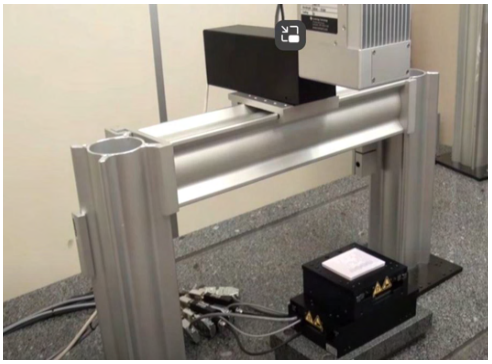
## Custom Optics and Integrated Assemblies

The laser beam of an SLA process must also be shaped, steered, focused and otherwise managed quickly. This is achieved with an intricate system of lenses, mirrors, other optics, opto-mechanical components, and sometimes motorized positioning. With our very experienced team of lens designers, opto-mechanical engineers and physicists that specialize in custom optical design and development, MKS can deliver complete integrated solutions that shape beams and quickly change focus and spot size for SLA applications.

SLA typically uses UV wavelengths, such as 355 nm, and MKS specializes in the design of thin film reflective, anti-reflective, partially reflective and high power coatings for laser optics down to 193 nm. MKS can manage build-to-print and build-to-specs or can design a custom solution to meet your application's requirements. And with our world-class manufacturing capabilities, MKS is able to scale quantities as needed and also provide cost-effective high-volume production.

## Motorized Positioners

A common device used to steer SLA lasers very quickly is a galvanometer scanner, or galvo. Although galvos can produce steering speeds of up to several meters per second with sharp corners, they have a limited field of view (FOV), on the order for 100-200 mm, and limited focal spot size of around 10-20 microns. By contrast, motorized linear positioners provide for a large FOV and allow for tight focal spots. Combining galvos and motorized positioners in a SLA system—by having positioners move the target or move the galvos—can take advantage of each of their features. MKS offers not only a full range of Newport™ motorized positioners but also Newport motion controllers that can synchronize the motion of galvos and positioners for high accuracy, precision and speed.



*Example setup of a Newport motion controller producing synchronized motion from galvo scanners (top) and Newport linear positioners (bottom) for laser processing applications.*

## MKS Products for Vat Polymerization

MKS offers many products that are broadly utilized in VPP. For more information, please visit www.newport.com or call +1 877-835-9620. Also, visit www.spectra-physics.com

## Compact UV Nanosecond Lasers


MKS offers the ideal laser for SLA: the Spectra-Physics Explorer One. This series of lasers is a compact, diode-pumped solid state (DPSS) ns UV laser which can deliver output power levels from 100 mW to 6 W, thereby covering all SLA requirements ranging from fine structures to larger surface areas. Complementing Explorer One's power levels is its high dynamic power range which ensures reliable and stable output power from approximately 10% of nominal to full nominal power—this allows a single laser to be utilized in an SLA machine while also providing versatility. Combining these power features with Explorer One's ns pulse widths, pulse repetition rates from single shot to hundreds of kHz, and typical rise times of ~90% of maximum power within 1 to 2 pulses enables fast SLA scanning. This laser also produces a very-close-to-ideal Gaussian beam ($M^2 < 1.3$) with power stability within 2% to ensure consistent high-resolution scans. Some units have performed reliably for years with uninterrupted use. Explorer One is also the most compact laser in its class, weighing just a few kg, making it a seamless fit for SLA systems.

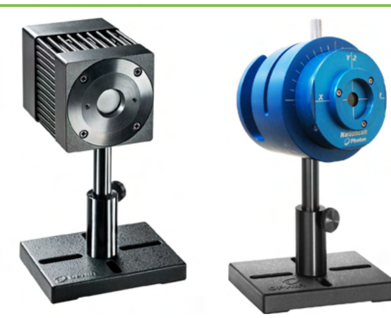
- 100 mW to 6 W power
- High dynamic power range
- Pulse widths <10, 12 or 15 ns
- Typical rise times of ~90% of max power within 1-2 pulses
- $M^2 < 1.3$, $TEM_{00}$
- Most compact laser in its class

## Compact Femtosecond Lasers


For 2PP additive manufacturing, ultrafast lasers are required. But unlike traditional SLA which requires UV, 2PP is typically achieved with visible to NIR wavelengths. The Spectra-Physics HighQ-2™ is an ultracompact, fs laser that delivers exceptional results for 2PP. Its high peak power and highly focusable Gaussian spatial beam profile enable micron- and sub-micron-scale precision. HighQ-2 is an air-cooled laser designed to provide a turn-key solution for 24/7 operation and is manufactured in a controlled, cleanroom environment for dependable, long life.

- 522 or 1045 nm wavelengths
- >35 kW (522 nm) or >80kW (1045 nm) peak power
- >0.65 W (522 nm) or >1.5 W (1045 nm) average power
- Pulse width <250 fs
- $M^2 < 1.15$, $TEM_{00}$
- Ultracompact, designed for 24/7 operation
- High uptime and low cost of ownership

## Laser Beam Analysis



Laser systems can degrade over time, leading to a reduction of output power or a shift in focus—this can result in inaccurate or inefficient polymerization. Some causes of degradation include the laser's thermal energy affecting optics, debris at the processing site, vibration and shock. Therefore, it is crucial to monitor the laser beam frequently, and the critical parameters of the laser should be checked before each important step of the laser manufacturing process. As the trusted leader in laser beam profiling and measurements, MKS offers a complete range of Ophir® instruments for beam characterization for any wavelength, at any power and for any beam diameter.

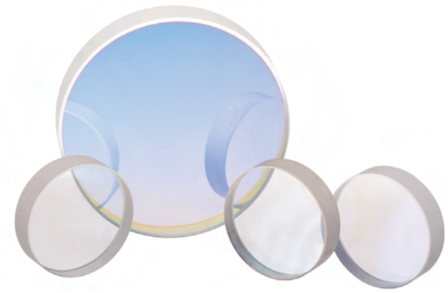
- Laser power and energy sensors measuring up to hundreds of kilowatts and hundreds of joules
- The most precisely calibrated power meters on the market
- Scanning slit and camera-based beam profilers to determine focus position, spot size and $M^2$

## Beam Profiling Cameras


An effective way to analyze beam profile is with a camera-based system. Ophir beam profiling cameras allow real-time viewing and measuring of a laser's structure in high resolution. Camera-based systems can also measure cross-sectional intensity of the laser and provide a complete 2-dimensional view of the laser mode.

- Spectral ranges from UV to mid-IR
- High-resolution, real-time viewing
- Highest accuracy measurements
- User-friendly application software with extensive analytical features included

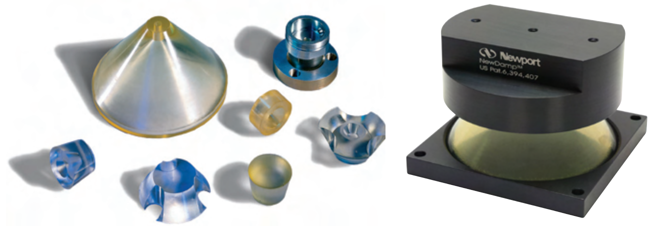
## High-Energy Laser Optics



Dozens of Newport standard catalog optics are designed to operate with high-energy lasers such as those used in SLA. Mirrors, lenses, beam splitter cubes and waveplates are readily available in various sizes and shapes whose substrate materials and coatings are optimized for UV wavelengths. These high-performing optics can withstand laser fluences to enable many solutions for SLA.

- Mirrors, lenses, beam splitter cubes, waveplates
- Optimized for UV wavelengths
- Extensive ultrafast optics selection
- LIDT (Laser Induced Damage Threshold) of up to 45 Joules per $cm^2$
- Various sizes and shapes

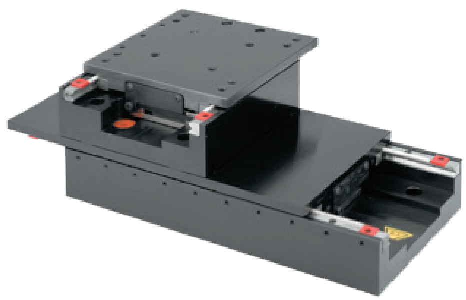
## Vibration Isolation




To improve SLA system performance, platforms may be mounted with vibration isolation. As the leader in vibration control and isolation, MKS offers Newport elastomer and pneumatic isolators that can also be built into equipment isolation supports and even custom machinery feet. A comprehensive set of standard catalog products are available, or MKS can work with you to understand your machinery characteristics such as load, shock response and resonance modes to design and provide a custom solution. Quantities can be scaled as needed through our world-class manufacturing capabilities.

- Elastomer dampers
- Pneumatic isolators
- Custom solutions and standard catalog products
- Scalable quantities

## Ultra-Precision Linear Motor Stages



The Newport XM is an exceptional series of linear positioners for SLA. They feature an ironless linear motor and crossed-roller bearings for smooth motion and sub-micron accuracy and repeatability. With the capability of providing minimum incremental motion as small as 1 nm, they are especially well suited for 2PP. Several models with various dimensions and travel ranges are available for the most demanding positioning requirements in high volume SLA production.

- 50- to 350-mm travel ranges
- 1-nm minimum incremental motion
- 100 to 300 N load capacities
- Sub-micron accuracy and repeatability

## Universal High-Performance Motion Controller

Newport's high-performance XPS-D series of motion controllers can control up to 8 axes of motion and offers movements ranging from basic to complex position-velocity-time, or PVT, motion trajectories through high-speed Ethernet TCP/IP interface. With its extensive analog and digital inputs and outputs, it can also monitor or synchronize with external events, including synchronizing galvos and motorized positioners for AM.

- Can synchronize galvos and positioners
- Up to 8 axes of high-performance, complex motion trajectories
- Extensive analog and digital I/O
- High-speed Ethernet TCP/IP interface

## Opto-Mechanical Components

Whenever optics are part of a laser system, they will have to be precisely positioned and steadily held over long periods of time. MKS offers the most comprehensive line of opto-mechanical components in the industry. Hundreds of Newport optical mounts and positioners at various levels of performance and cost are readily available.

- Mirror mounts, lens positioners and other optical mounts
- Linear and rotary positioners
- Post and pedestal assemblies
- Stainless steel and aluminum

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## WHY MKS?

**CRITICAL TECHNOLOGIES**

World-class technology and development capabilities for leading-edge processes

**PROVEN PARTNER**

Recognized leader delivering innovative, reliable solutions for our customers' most complex problems

**OPERATIONAL EXCELLENCE**

Consistent execution across all aspects of our business

**COMPREHENSIVE PORTFOLIO**

Largest breadth of product and service solutions for the markets we serve


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