Figure 1. DPSS Lasers ultraviolet lasers feature a compact laser head and a long lifetime for 24/7 industrial applications, which place specific requirements on the internal opto-mechanics. (Image courtesy of DPSS Lasers Inc.)

Custom Optomechanics *in Industrial UV Lasers*

Figure 2. The 0.5 inch ball slide linear translation stage customized for use inside the DPSS Lasers cavity – note the absence of any anodizing.

Reliability and longevity directly impact the cost of using Q-switched, diode pumped, solid state, ultraviolet lasers in industrial applications. Damage to the intracavity harmonic crystal is often the major limiting factor in the lifetime of these lasers.

Frequency Harmonics – Efficiency vs. Photodamage

The majority of DPSS style lasers are based on neodymium (Nd) doped glass or crystal (e.g.,YLF, YVO_4) which have a strong emission line around 1064 nm. For visible and ultraviolet applications, the 1064 nm fundamental has to be frequency doubled or tripled to 532 nm or 355 nm respectively, using non-linear crystals such as BBO and LBO. Frequency tripling involves both a frequency doubling crystal followed by a sum frequency generating (SFG) crystal. These non-linear, two-photon processes critically require high intensity (fluence), particularly for frequency tripling where there are two of these processes in tandem.

For continuous-wave lasers, the requirement for high fluence is usually met by placing the crystal(s) at an intracavity beam waist, since the circulating power is much higher than the output power. For pulsed lasers (both Q-switched and mode-locked) the high peak power of the pulses means that extra-cavity harmonic generation can be used. However, at the power levels used for marking and precision micromachining applications, this often requires focusing the laser to a small spot in the crystal. Depending on the power and spot size, photodamage to the crystal can occur in a few hundred hours or less in 355 nm lasers. So, it is common in commercial lasers to periodically move the non-linear crystal to a new "sweet spot," either manually or via automated control. In spite of this brute force "consumable" approach, crystal burnout is a leading cause of power loss and failure in many commercial DPSS style lasers.

DPSS Lasers use a different approach in their Q-switched UV lasers. They place the non-linear crystals intra-cavity, which means that a larger area beam can be used. This avoids the need to create a very small beam waist in the cavity, simplifying optical design and alignment. And, by using a larger area of the crystal, photodamage probability is lowered. More importantly, extensive life testing at the company showed that damage was a cumulative mechanism, presumably caused by non-radiative processes, e.g., heat and stress build-up. These tests proved that, instead of waiting for damage to occur and then moving the crystals, a much longer overall crystal lifetime could be obtained by slowly, but continuously, moving the crystals, i.e., sweeping the crystals back and forth perpendicular to the beam direction.

Ball Slide Translation Stage

In their latest generation of Q-switched, ultraviolet lasers, DPSS Lasers worked with Siskiyou to define a mechanism to perform this slow, repetitive motion. However, cost was a major factor in the highly competitive industrial laser marketplace.

DPSS Lasers defined several critical requirements for a translation stage to move the doubling and tripling crystals. These included the use of only UV compatible materials, up to 12 mm range of

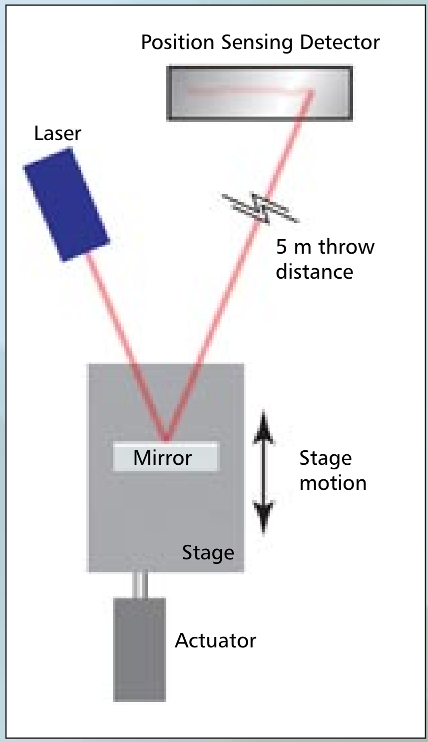

Figure 3. Motion linearity is checked for every batch of stages using reflection of a laser beam and a long throw distance.

Figure 4. An economical solution to position feedback is provided by mounting a low-profile circuit board with a linear potentiometer, inside the Siskiyou actuator.

linear travel, and the ability to hold position with a DC motorized actuator. Siskiyou manufacture several types of linear translation stage, with the trade-offs being performance (linearity) versus cost. The highest performance is undoubtedly obtained with crossed-roller bearing stages, which offer high load-bearing capacity and superior precision. However, these can cost nearly twice as much as other stage types. Conversely, the lowest cost and performance is usually obtained using a dovetail mechanism, where the two principal components slide against each other directly. These provide no means to adjust any play due to natural machining tolerances.

For this application, Siskiyou recommended a custom, mid-range stage based on an existing ball bearing slide model with a 0.5 inch (13 mm) motion range (Figure 2). Motion is controlled by a linear actuator that pushes the stage in opposition to some type of (pre-load) return spring. A key custom design element was the use of heavy duty return springs to provide maximum pre-tension, and to hold the stage static position while the motion actuator was unpowered and stationary.

Impact of Motion Linearity on Phase Matching

Although the motion linearity (wobble, pitch and yaw) were not formally specified for the custom stage or its standard format predecessor, dialog between engineers at both companies concluded that the linearity of this stage would be sufficient to meet the linearity needs. And, at first this proved to be the case. However, in later production, some of the lasers could not consistently achieve target ultraviolet power, and showed power fluctuations in the ultraviolet output, but not the fundamental. This meant there were variations in the harmonic conversion efficiency which was soon tracked to the linearity of the stage motion. Specifically, the problem was identified to be small motion non-linearities – minor pitch and roll motion.

The reason for this sensitivity is that harmonic generation requires a condition called phase matching. Dispersion in most solid materials means that the fundamental (1064 nm) and doubled (532 nm) wavelengths will have different group velocities. But, in order to coherently build up power at the doubled wavelength, a zero phase slip between the two wavelengths must be maintained. In the mixing crystal, the situation is potentially more challenging where a constant phase relationship must be maintained for three wavelengths (1064 nm, 532 nm, and 355 nm). This phase matching is typically accomplished by using a birefringent mixing crystal, where the index of refraction (and hence the group velocity) depends on the polarization state of the beams and the angle of the crystal relative to the beams.

It turned out that minor non-linearities in the motion of some of the stages meant that the angle of the crystals varied slightly – where the doubling and tripling efficiencies are particularly sensitive to x and y. This conclusion led to more dialog between engineers at the two companies.

Calculations confirmed that the ball slide stage should provide the requisite motion linearity, so a redesign was not required. Rather, a new assembly protocol and a confirming QC test were defined to ensure that all stages met the specification required by DPSS Lasers. The details are proprietary, but in simple terms, the pressure (i.e., tightness) on the ball bearings is a key parameter. Too much pressure and the stage motion cannot be reliably driven by the low voltage actuators defined by DPSS Lasers. However, applying too little pressure allows wobble in the motion, i.e. pitch and roll. So a key assembly protocol was the sequence of tightening the screws and the application of a precisely measured torque to each of these screws.

Statistical random samples from each batch of production stages are now subjected to a simple but reliable testing protocol, based on a long optical leverage as shown simplistically in Figure 3. A planar mirror is temporarily mounted on the stage being tested. Position sensing detectors are located at a long (several meters) distance from the stage. The stage is then repeatedly run in a sequence of continuous and stop/start motions during which the laser spot must stay within a certain locus to confirm the angular fidelity required.

DC Motorized Actuator With Low Cost Feedback

The actuator required to automatically drive each of these stages also required customization. A DC motor was chosen for several reasons. Piezo actuators do not provide the requisite travel range and stepper motors require constant power in order to hold position, but it was decided to minimize the power budget for the laser. Siskiyou manufactures a range of DC motors with motion controlled by an industry standard 12-volt pulsing. However, DPSS Lasers wanted to operate these motors using only 6 volts to enable slower motion (i.e., higher resolution) and to further minimize power budget. As already noted, however, the stages were also equipped with heavy return springs.

Fortunately, there is a large overhead built into the design of these DC motors and it turned out that there is no problem operating them at 6 volts. But to ensure there are no issues in the field, Siskiyou tests these extensively with voltages down in the 1 to 3 volt range, while they are attached to the stages, using a precision laser interferometer and a retroreflection.

Just as important, DPSS Lasers needed to configure these motorized actuators for closed-loop operation. Many users of

DC motors accomplish this by using some type of encoder to measure position. However, they did not want the added size and cost of using encoders in their compact laser heads. Again, a dialog between the two companies resulted in a design where Siskiyou assembles the motors with a compact circuit board incorporating a linear potentiometer all supplied by DPSS Lasers. This is located inside the motor assembly so that the spring-loaded potentiometer pin rides against the "key indicator." This is a low-profile metal tongue that protrudes from the side of the actuator in many commercial actuators. This provides the (proprietary) feedback resolution needed to fully exploit the slow scanning and hence maximize the lifetime of the harmonic crystals.

Qualified Materials – Pristine Cavity

Another overarching theme in this project is the use of materials that are UV laser compatible. It is well-established that a common cause of early failure in UV lasers is failure of optical surfaces, many of which carry dielectric coatings. The problem arises because any dust or chemical contamination tends to ride along a laser beam and eventually reaches an optical surface. This leads to absorption of laser light at the surface, resulting in damage that further increases absorption, etc. In lasers intended for industrial applications, it is simply not practical to allow cleaning of the optics by the end user, who rightly wants to use the laser as a 24/7 tool, not a delicate scientific instrument. So instead, UV laser manufacturers take steps to eliminate the possibility of any cavity contamination or outgassing. This typically involves sealing the cavity, ensuring there are no mechanisms to generate contamination inside, and some type of cleaner inside the laser head to actively remove contamination.

The stages and actuators thus had to be made only with materials qualified by DPSS Lasers. This meant using the same materials that Siskiyou uses in vacuum compatible optomechanics, i.e., no organics and using crytox as the only lubricant. In addition, it required no anodizing. Normally the majority of stages, mounts and other optomechanics are black anodized to minimize scattered light issues. But, it turns out that when black anodized (oxidized) aluminum is exposed to small amounts of scattered UV laser light inside a sealed cavity, it eventually creates traces of dust. As shown in Figure 2, this is the reason why the stages are neither anodized nor powder coated.

Summary

In recent years, there has been a growing demand for ultraviolet lasers in applications such as micromachining and marking. This is because these lasers can deliver high spatial resolution and a minimized heat affected zone (HAZ). Improved laser reliability and lower cost of ownership have been keys to this market growth. While many might think of UV DPSS lasers as a mature technology, this work shows that they can be enhanced through the use of innovative designs and the clever use of components.

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