*Journal of Directed Energy*, **4**, Fall 2010, 110–118

# Development of High-Brightness Thin Disk Lasers

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*Testing of a multidisk thin-disk laser has been conducted using a unique multipass resonator that provides aberration and mode control as well as high gain. The disk modules used were derived from commercial thin disk lasers. The laser consistently produced a power level of 28 kW, beam quality of 2.7, and an optical-to-optical efficiency of 43%. No adaptive optics are required to achieve these results. Based on these results, a modified resonator should achieve single-mode operation with optical-to-optical efficiency of 55% and beam quality of less than 2.0 without adaptive optics. Disk scaling studies have shown that amplified spontaneous emission can be controlled to a disk size consistent with 100 kW or greater power levels.*

**KEYWORDS:** High brightness laser, High power lasers, Mode control, Thin disk laser, Unstable resonator

## 1. Introduction

The "holy grail" for laser weapons would be an electric laser operating for long durations at high power, with near diffraction–limited beam quality and high electrical efficiency, and providing high reliability, availability, and maintainability (RAM) at an affordable price. Boeing has pursued the development of a thin disk laser (TDL) as a leading contender to achieve all of these characteristics. The Boeing TDL uses a gain medium derived from commercially available Trumpf lasers that operate continually in industrial environments, providing a unique potential for RAM and affordability. These gain media are coupled through a unique high-performance resonator to create a single high-brightness beam from the multiple individual laser heads (gain modules). This resonator requires no high-order active correction, and incorporates "optical shunts" that provide passive protection to critical laser elements in the event of a single point failure. Moreover, the resonator is largely scale invariant, allowing low-risk scaling in power based on gain module scaling. The end result is a laser that has demonstrated, even in its early implementation, the highest combined power and brightness that has the potential to develop into the laser of choice for military missions.

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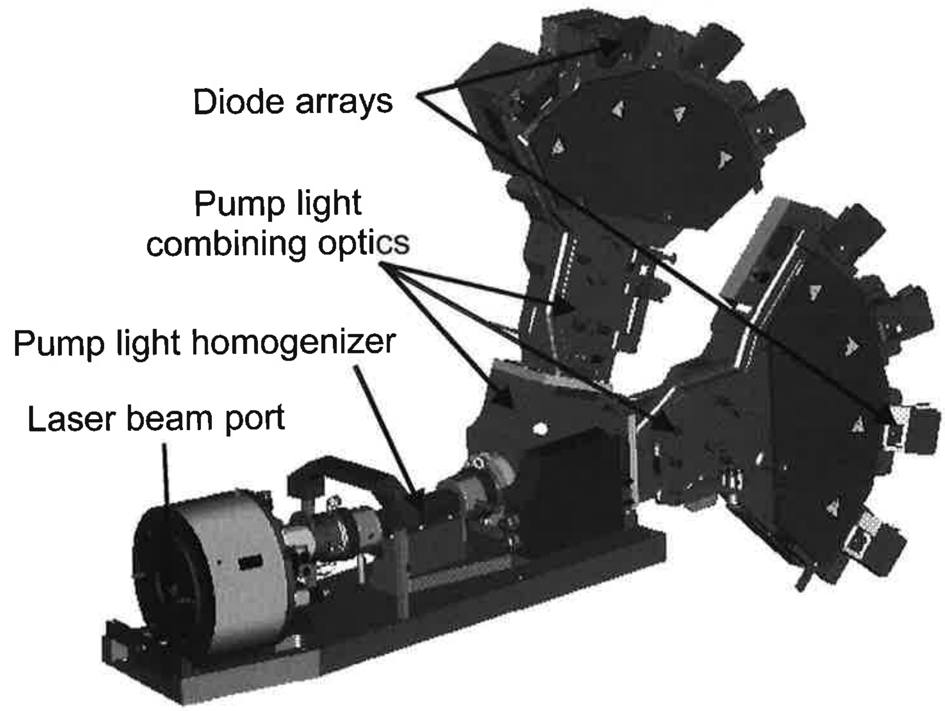


Fig. 1. Trumpf modules provide modified off-the-shelf building block.

## 2. High-Brightness, Thin-Disk Laser Architecture

The high brightness TDL is architected with a series of identical disks contained in independent gain modules. Each module includes diode pumping and thermal management for a single disk. To reduce costs and take advantage of the integration of a production laser device, a modified off-the-shelf (MOTS) industrial laser produced by Trumpf (Figure 1) has been used as a key building block. (The Trumpf module design is property of Trumpf Inc. Information is available on the company website at www.us.trumpf.com.) In this unit, the diode pumping is produced through free-space combining and homogenization of diode bars assembled into arrays. While the ytterbium (Yb):yttrium aluminum garnet (YAG) disks are highly doped to achieve high diode absorptivity, the extremely thin disk, typically around 0.1 mm, limits diode absorption per pass. It is therefore necessary to direct the diode pump light many times through the disk to achieve high absorption. This is accomplished with optics that "step" the pump beam orientation around repeatedly, thereby achieving extremely uniform disk pumping. The composite of these multiple diode pump passes is a pump intensity profile that has a uniform central region and a super-Gaussian profile toward its edge.

The TDL uses a standing wave resonator (SWR), which has been used successfully in a number of high power/high brightness lasers. (Resonator configuration is covered by Boeing patents issued and pending.) This resonator can produce a circular beam with a

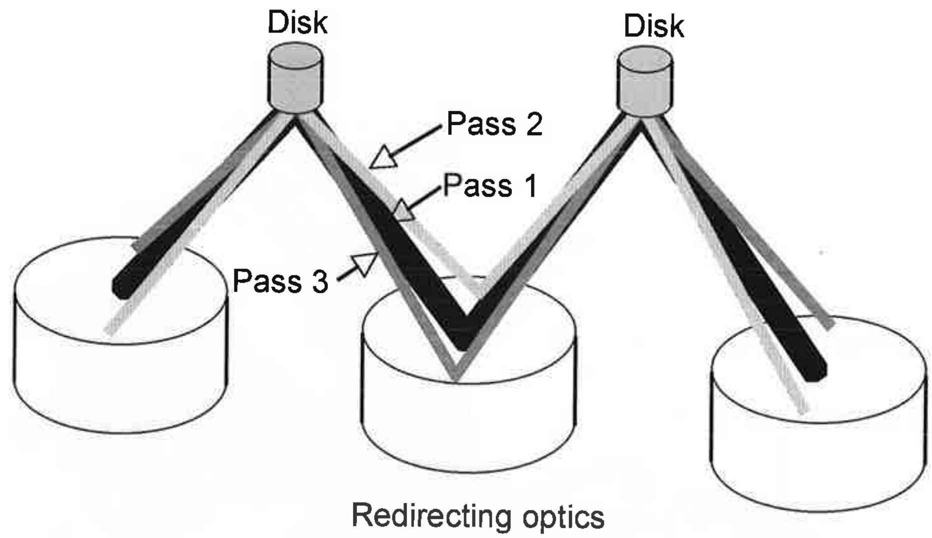


**Fig. 2.** Multiple beams intercept each disk.

central obscuration with low clipping and coring losses, which is well suited for projection through conventional telescopes and beam directors. Both for reasons of integration with the beam projector and for alignment sensitivity, which increases as the magnification decreases in an SWR, it is desirable to have a magnification of around 2 or greater. SWR resonators operating in this magnification range are also known to achieve good mode selectivity, another requirement for high brightness.

Given the limits on laser gain in the disk medium and the extreme thinness of the disks, achieving the gain within the resonator needed to match the magnification and beam outcoupling fraction can require over 100 passes through a disk or disks. When used for industrial applications (low brightness), commercial TDLs can provide 4 kW per disk, and testing to be discussed in the following has already produced 3 kW per disk at high brightness. In short, the number of disks is determined by the desired power and the power available per disk, while the number of disk strikes is determined by the required amplification as set by the resonator magnification. Multiple passes may be directed through each disk (Figure 2) utilizing the same redirecting optics between each disk. In order to compensate for nonaxisymmetric aberrations within the resonator, the beams may be rotated (Figure 3) between passes so as to achieve partially compensation and cancellation. Because of the rapid thermal response of the thin disks, residual axisymmetric aberrations can be corrected through a static-phase plate.

Since the diode pump intensity profile is super-Gaussian, the optimum extraction efficiency will be achievable in a single mode that matches the profile. To achieve that, the laser beam is outcoupled through a gradient reflectivity mirror (GRM) (Figure 4) having a reflectivity profile that matches the diode pump profile. The GRM reflects the return beam into the resonator and transmits the laser beam through the optic. For long-duration lasing, an externally cooled GRM would be fabricated out of a high-conductivity, low-absorption material. In contrast to a conventional scraper and return mirror set, there is no "hard

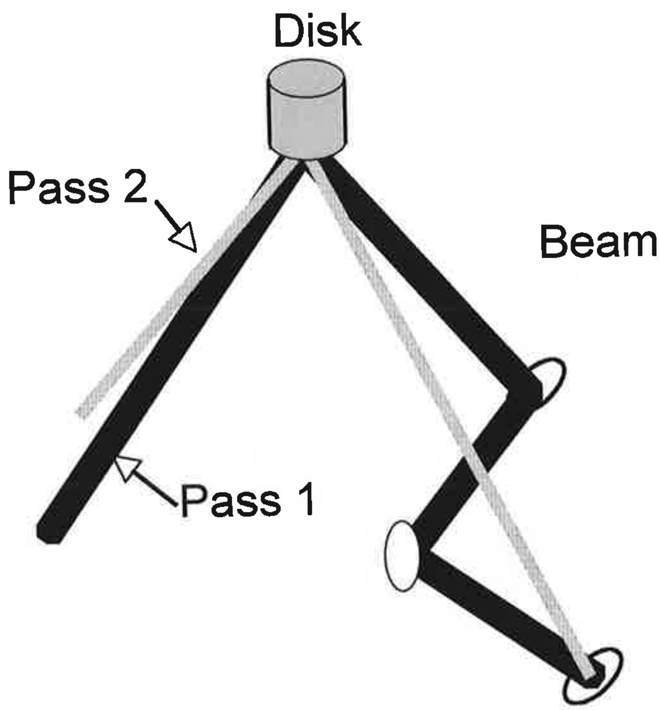


**Fig. 3.** Beam rotation compensates for internal aberrations.

edge" to the beam. This reduces the diffractive effects as the beam propagates through the resonator. Diffractive ripple on the beam can impact extraction and thermal loading, and hence produce a more aberrated beam.

The TDL disk, having extremely low mass, is sensitive to even short-duration drop-outs of lasing. To ensure that this does not affect the TDL, each disk has an auxiliary resonator (AR) that extracts power when there is excessive gain in the disk or a region of the disk. The AR is a stable V-resonator (Figure 5) with an outcoupler reflectivity selected to thermally protect the disk if the main resonator (MR) is not operating while minimizing the power extracted while the MR is running. Since the AR is a stable resonator, the power it outcouples is not useful for applications requiring high brightness.

## 3. High-Power Laser Demonstration

As an initial proof-of-concept for this approach, the resonator concepts discussed above have been implemented in a laser having 10 disks and two beams (Figure 6) and operating at a magnification of 1.42. This laser was not expected to achieve optimal performance in terms of efficiency nor beam quality, but was a step toward those goals. The laser was implemented in a modular fashion using standard optic mounts and vacuum enclosure parts. The 10 disk modules are closely spaced at one end of a bench and are mechanically mounted so that minimal fine position adjustment is required for alignment. Similarly,

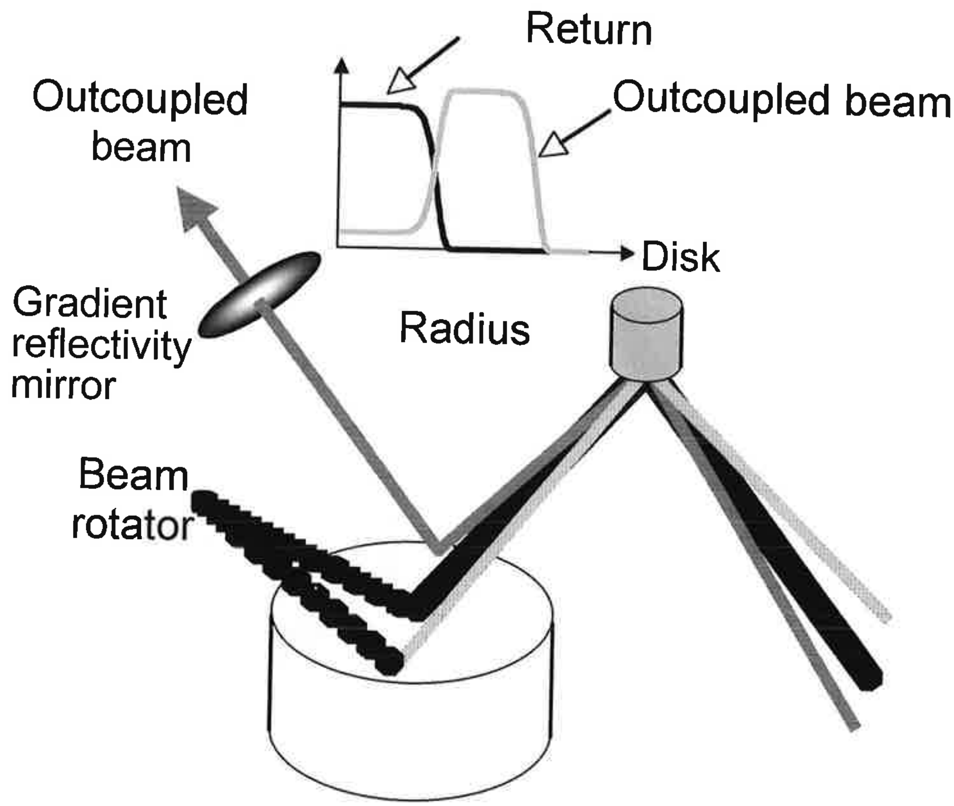


**Fig. 4.** Gradient reflectivity mirror produces super-Gaussian beam.

the redirecting optics mounts are adjustable in position without breaking vacuum. The resonator does not use adaptive optics, instead relying on optical compensation to cancel aberrations.

The design of the resonator accounts for a power-dependent focus contributed by the disks, with the objective of achieving best beam quality at full optical power. A static corrector plate is also provided to compensate for some higher-order aberrations of the disks and optics. The design of all of these features is accomplished through Boeing's version of the OSSim (Optical Systems Simulation) code that has been tailored to model these important features of TDL operation. This code has also been adapted so that full interferometric data from the resonator can be utilized in the performance optimization process.

Because of the competition between the MR and ARs, the TDL operates at high efficiency over a relatively narrow range of diode optical power, with the main beam at essentially zero power until diode optical power exceeds some threshold. The demonstrated optical-to-optical (o-o) efficiency reached 43% for the MR and 57% for the MR and ARs. The best operating condition produces a power of 28 kW in the MR at a beam quality of 2.7. (Beam quality is computed from a far-field beam in accordance with JHPSSL Technical Notes for Laser Characterization.[1]) Under these conditions a primary mode and several secondary

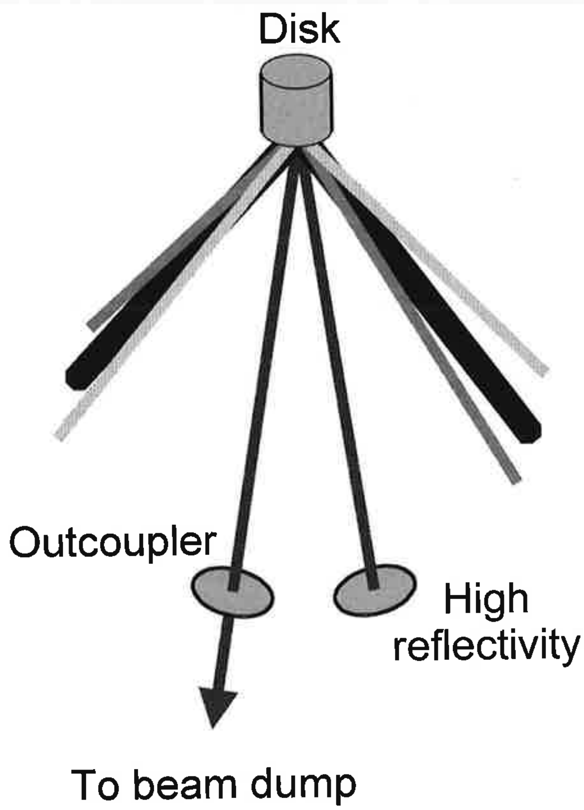


**Fig. 5.** Auxiliary resonators provide thermal protection to disks.

modes are running as expected at the relatively low resonator magnification being used. Analysis of this test series indicated that the ARs had reflectivities slightly above optimum, and that reduction of these reflectivities by less than 1% would lead to a transfer of 25% of the total power from the ARs to the MR under maximum brightness conditions. This extreme sensitivity comes from the active competition for extraction between the two types of resonators. This gives a projected MR o-o efficiency of 55%, close to the 60% seen in TDLs operating with stable resonators. At the same time, with further modification of the resonator optical passes, it is projected that single-mode operation will be achievable with a beam quality of less than 2.0.

Power and beam quality measurements are extremely stable and reproducible. Replicated runs at the best brightness point show reproducibility of power to within 1%; under these conditions the beam quality measurements show reproducibility to ±0.05 beam quality units within a test run. Since it was indicated that several modes were running, no effort was made to estimate or demonstrate the correctability of the beam using adaptive optics external to the resonator. At higher magnification and with single-mode operations, this approach to improved beam quality should be useful since the dominant aberrations are associated with thermal distortions of the disks and optics, and these are slowly varying with time.

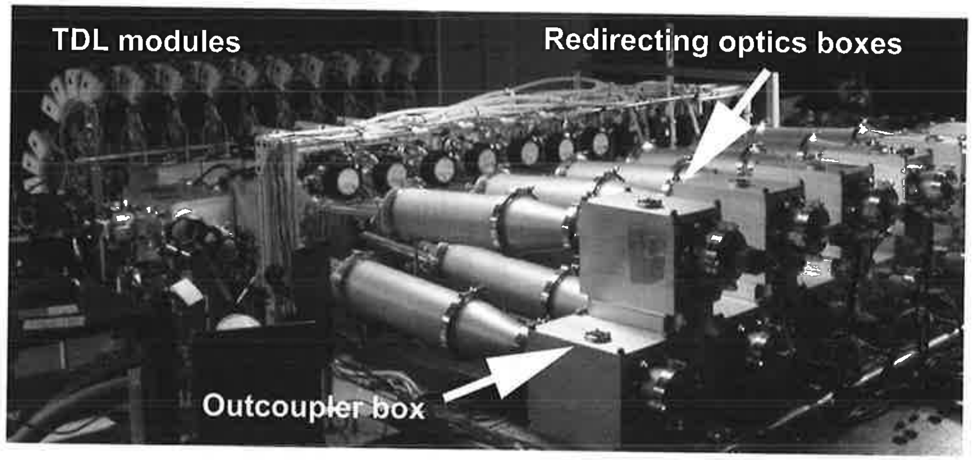


**Fig. 6.** TDL lab unit is flexible test bed for laser development.

## 4. Thin-Disk Laser Scaling

Power scaling in TDLs can be accomplished in two distinctly different ways: gain module replication and gain module growth. At first glance, replication would appear simpler, since you can use the same available building block and can reduce the number of beam passes through the resonator by taking advantage of the additional gain path through the additional disks. In reality, a negative effect occurs, which is that the beam intensity also increases as the gain module number increase. Because of the excited state spectrum of Yb and the high value of $I_{SAT}$, it is necessary to operate with relatively high beam intensity on the disk to achieve high efficiency. Adding more disks becomes both a thermal and beam aberration issue. In turn, the beam aberration effects tend to reduce mode selectivity and make it increasingly difficult to achieve single-mode operation.

The key issue for the disk scaling approach is amplified spontaneous emission (ASE), which limits disk size. If ASE could be controlled, laser power scaling by disk areal scaling would leave the resonator architecturally the same at all power levels, and would leave the beam flux independent of power. Both of these factors reduce the risk of power scaling. Power scaling effectively becomes a matter of building a larger disk and gain module, and inserting those into an existing proven resonator with only minor changes as needed to provide room for growth in disk and beam size.

Given the approximately 100:1 aspect ratio of a thin disk, in which the laser resonator gain is taken in the short direction, ASE can be a significant limitation even for relatively small disks. Several approaches are available to suppress ASE; one promising approach, in which an undoped YAG cap was added to the disk, was tested. In this test an undoped YAG cap was added to a Yb-doped disk, with the cap being significantly thicker than the disk. The exterior surface of the doped disk had high-reflectance (HR) coatings at both the diode pump and lasing wavelengths and orientations; the exterior surface of the undoped cap had antireflection (AR) coatings for the same conditions.

Based on the operating conditions encountered in the high-brightness tests described previously, a 100-kW–class laser should operate with a disk diameter and loaded gain

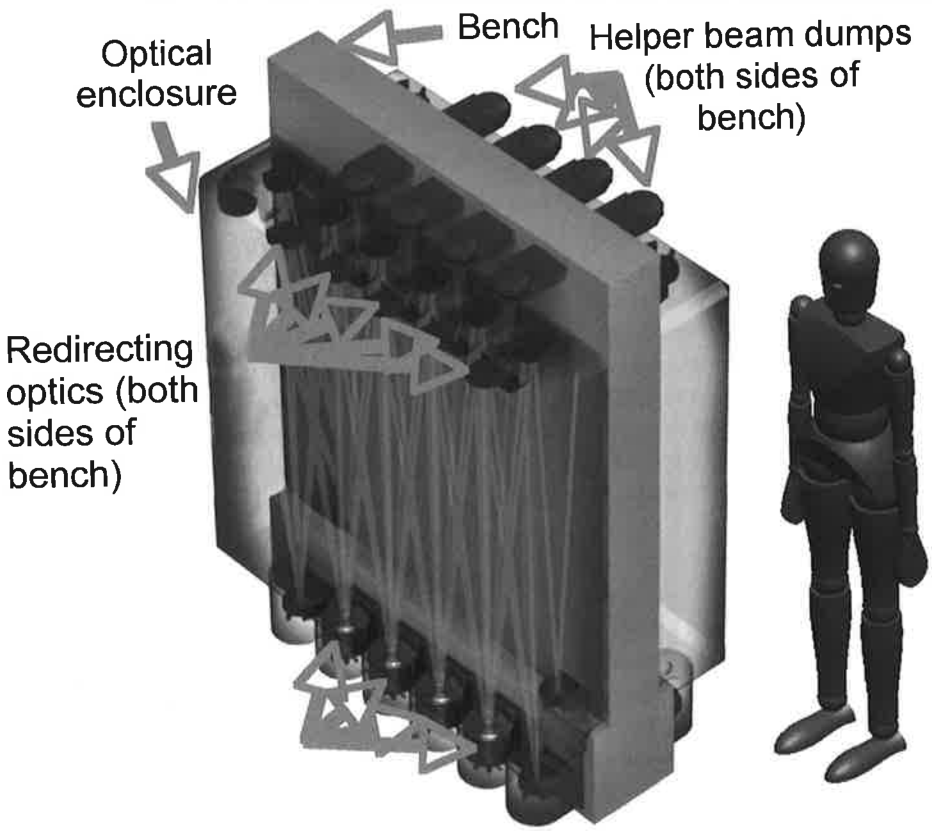


**Fig. 7.** High power TDL concept.

giving a gain-diameter product of approximately 1.8 (dimensionless). For that condition, there is a loss of approximately 40% in slope efficiency without a cap and essentially no loss with a cap.

At some point in the process of scaling up disk diameters, this approach will fail to be fully effective in suppressing ASE. Above that diameter, ceramic disks may be produced that provide further ASE suppression through segmenting the disk by inclusion of a dopant that absorbs at 1.03 μm in selected regions of the disk. The segmentation is performed in a way that preserves a single-mode structure for the outcoupled beam. As an example, $Cr^{+4}$ is a highly effective YAG dopant for absorption at the Yb lasing wavelength. Depending on the absorbing material selected, the struts may also prove strongly absorbing at the diode pump wavelength. To ensure that the struts are thermally neutral and therefore do not contribute to structural deformation of the disk and resulting optical aberrations, a partially reflective coating is placed on them to reflect a portion of the diode pump light away from the struts.

It is possible that the struts may have some impact on aberrations and mode selection, in which case a master-oscillator (MO), power-amplifier (PA) architecture may be utilized. In such a MOPA, the MO would be of a power consistent with using disks that do not incorporate internal struts, and the PA could then operate with disks with struts without impacting mode control.

## 5. Plan for High Brightness Lasers

The TDL lends itself to simple, accessible, and maintainable laser device packaging. One such concept (Figure 7) uses a multipass resonator with fiber-pumped disks arranged on both sides of a bench. The resonator operates at a magnification sufficient to produce single-mode operation. Beam quality is estimated to be better than 2.0 without adaptive optics, and correctable to 1.2 with adaptive optics external to the resonator. Internal to the resonator, only corrector plates are used for aberration correction.

In accordance with the disk areal scaling approach for higher powers, scaling entails replacement of the disks and gain modules with larger ones, with the active disk diameter scaling approximately as the square root of power. The larger intracavity beam will require correspondingly larger resonator optics, and the gain module height and diameter will scale approximately as the active disk diameter to allow for diode pump beam management.

## 6. Summary

Boeing has demonstrated a high brightness/high power laser based on MOTS TDLs that is far simpler and more efficient than slab lasers of comparable power and, with further development, should meet or exceed projections for high-power fiber lasers and diode-pumped alkali lasers. Testing to date has demonstrated excellent repeatability and reliability. An innovative scaling approach opens up the potential of higher power solid-state lasers with low risk in resonator development.

### Reference

1. Northrop Grumman Corporation, JHPSSL Technical Notes for Laser Characterization, Technical Evaluation Committee, Joint High Power Solid-State Laser Program, September 30, 2004.

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