Monolithic solid-state lasers for spaceflight

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ABSTRACT

A new solution for building high power, solid state lasers for space flight is to fabricate the whole laser resonator in a single (monolithic) structure or alternatively to build a contiguous diffusion bonded or welded structure. Monolithic lasers provide numerous advantages for space flight solid-state lasers by minimizing misalignment concerns. The closed cavity is immune to contamination. The number of components is minimized thus increasing reliability. Bragg mirrors serve as the high reflector and output coupler thus minimizing optical coatings and coating damage. The Bragg mirrors also provide spectral and spatial mode selection for high fidelity. The monolithic structure allows short cavities resulting in short pulses. Passive saturable absorber Q-switches provide a soft aperture for spatial mode filtering and improved pointing stability. We will review our recent commercial and in-house developments toward fully monolithic solid-state lasers.

Keywords: Solid-state lasers, Q-switch, Space flight lasers
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1. INTRODUCTION

There are currently three operational lidar systems from NASA orbiting the Earth, the Moon and the planet Mercury gathering scientific data and images to form a better understanding of our Earth and solar system. All these lidar systems were built on high power quasi-continuous wave (QCW) laser-diode-array (LDA) pumped solid-state laser (SSL) architectures. These QCW pumped SSL laser systems became the enabling technology that led to a series of successful spaceborne lidar systems for Earth observing and planetary exploration. We recently published a summary[1] of the laser architecture and performance for these missions as well as plans for future missions.

The next generation of space-based laser instruments can greatly benefit from reduced size, weight, power and cost by using new technological methods for component integration. The ultimate integration is a monolithic (i.e. one piece) system. The semiconductor laser and photonics industry, driven by the ever-increasing telecommunications market, is experiencing a revolution through the use of monolithic photonic integrated circuits. Recent results[2] include the monolithic integration of 40 tunable distributed feedback lasers, 80 nested Mach-Zehnder-modulators, and other elements totaling over 1700 functions on a single InP-based chip that is capable of delivering 2.25 Tb/s. A crystal fiber laser[3] was an early fully monolithic demonstration. Similarly, fusion-spliced glass fiber lasers provide a robust near-monolithic architecture. Here too, recent developments have led to a more fully monolithic (splice-less cavity) architecture[4,5]. The first popular monolithic solid-state lasers are the non-planar ring oscillator[6] and the microchip laser[7]. An impressive recent monolithic laser example is a monolithic 12 mJ Q-switched Nd:YAG laser[8] that could be directly applicable to space flight lasers. In this paper, we discuss ideas and technology for further advances in monolithic solid-state lasers – with special emphasis on space flight application.

2. VBG MONOLITHIC YB GLASS LASER

We recently demonstrated a monolithic continuous-wave (CW) Photo-Thermo-Refractive (PTR) glass laser with a Volume Bragg Grating (VBG) resonator.[9,10,11] The unique optical properties of VBGs recorded in PTR[12,13] provide

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extremely narrow spectral and angular selectivity combined with a high tolerance to laser radiation and harsh environmental conditions.[14,15] These elements were successfully used as narrow band output couplers and reflective mirrors in laser resonators for spectral narrowing of different types of lasers to the level of a few picometers. A similar fully-space-qualified VBG output coupler element is used in the ICESat-2 ATLAS space-flight lasers[16]. In the ATLAS laser, the single VBG optic: 1) is the oscillator output coupler 2) provides wavelength narrowing and 3) provides wavelength locking. The PTR glass VBG element alone provides this multifunction benefit.

By doping the PTR glass with a suitable lasing atomic element – for example ytterbium (Yb) - we fabricate an entire laser in a single piece of glass (i.e. monolithic). We demonstrated (Figure 1) a fully monolithic 0.3×0.3×15 mm^3 Yb doped PTR glass Distributed FeedBack (DFB) single-frequency narrow-linewidth (<250 kHz) laser with a maximum continuous-wave (CW) power of 150 mW and high beam quality ($M^2 = 1.34$).[17] The laser output power and wavelength tuning at various pump power is shown in Figure 2.

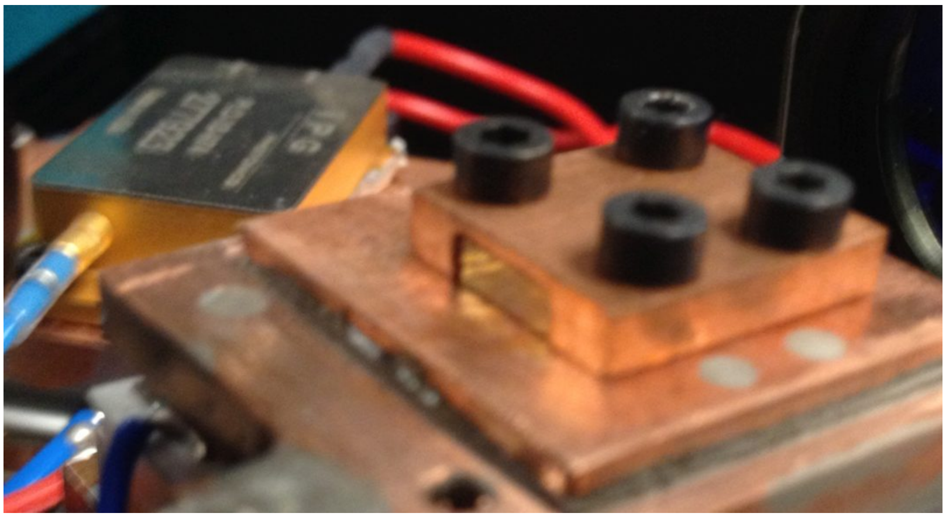
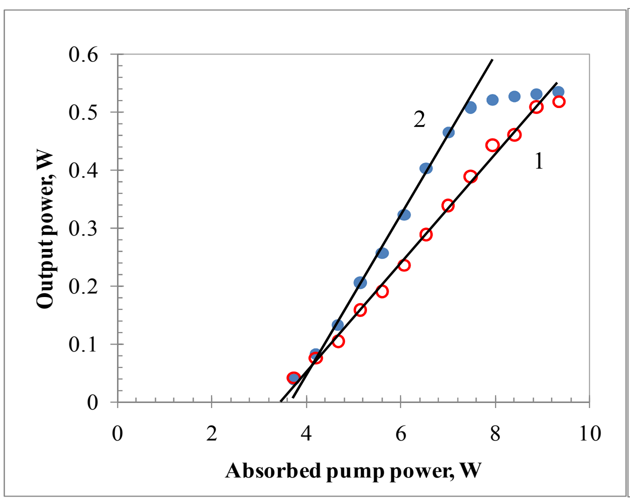


Figure 1. Optigrate's prototype continuous-wave, tunable, single-frequency laser in a single piece of Yb-doped PTR glass funded by NASA and DARPA. Holographic gratings are the mirrors and provide wavelength tuning and narrowing.



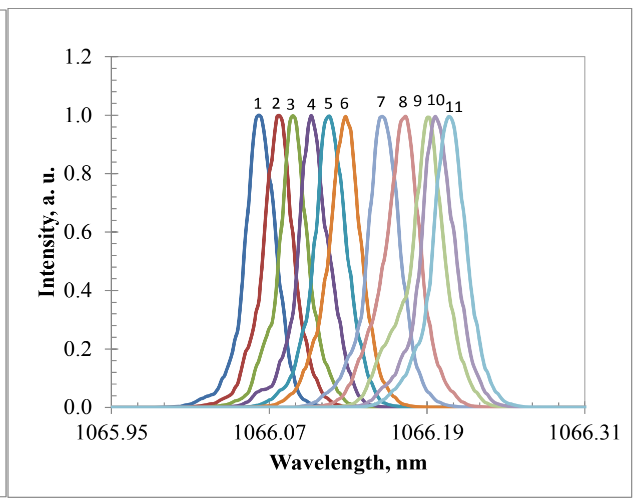


Figure 2. Output parameters of Yb:DFB laser. (a) Output power vs absorbed pump power for backward (1) and forward (2) lasing; (b) Emission spectra at different levels of absorbed pump power: **1.** 3.6 W; **2.** 4.2 W; **3.** 4.7 W; **4.** 5.2 W; **5.** 5.6 W; **6.** 6 W; **7.** 6.5 W; **8.** 7 W; **9.** 7.5 W; **10.** 8 W; **11.** 8.5 W

Although this first demonstration in PTR glass is low power, optimized Yb and Nd doped glass CW and pulsed lasers are known to produce world-record powers and pulse energies.

3. ADVANTAGES OF MONOLITHIC LASERS

Monolithic solid-state lasers provide a benefit in almost every aspect of laser engineering. Although not a necessity, it is much more likely that the monolithic laser fabrication process will be more tightly controlled through the use of automation. This helps improve reliability through strict engineering quality control processes that can be difficult to implement in separate bulk component laser manufacturing. This could be noted as a possible disadvantage – since upgrades or repairs to the laser are difficult. However, the history of semiconductor integrated circuits and lasers has shown the viability of the monolithic system philosophy where there is a strong market pull. A monolithic system typically shifts the manufacturing focus toward a repeatable process that is also more conducive to computerized automation. The direct advantages of monolithic manufacturing for the laser system are as follows. The DFB/DBR helps with spectral narrowing, spectral stability and single frequency operation. A passive saturable-absorber Q-switche provides a soft aperture for spatial-mode-filtering giving high beam-quality and improved pointing-stability. The passive Q-switch also eliminates the need for a high voltage power supply and associated high-voltage issues (arcing, Paschen's law breakdown). The short cavity provides short optical pulses from Q-switching and high repetition rates for mode-locked operation. In addition, a short cavity may reduce detrimental nonlinear effects. When Bragg-grating mirrors serve as high reflector and output coupler, the number of surfaces with optical coatings can be reduced. The optical coating requirement is reduced to anti-reflection coatings to minimize Fresnel reflections for the pump and lasing wavelengths. In addition, Brewster's angle interfaces could possibly be used for, or in conjunction with, polarization selection. This greatly reduces the issue of laser damage to optical coatings. A closed laser cavity is immune to contamination inside laser cavity, where typically the highest fluence is present. A monolithic solid-state laser will typically use multiple fiber-coupled pump lasers to improve reliability through pump laser redundancy and de-rating. A laser array also provides improved reliability through redundancy. The monolithic design minimizes number of components for improved reliability and nearly eliminates misalignment concerns of the laser resonator. Active forced-air cooling through vent holes or integrated heat-pipes in the substrate can be used in the thermal management design.

4. TYPES OF MONOLITHIC SOLID-STATE LASERS

Monolithic solid-state lasers have been in use for decades. To date, however, the laser energy has been very difficult to scale in a monolithic solid-state laser architecture. New fabrication methods and laser architectures are promising. In addition to our PTR laser approach described above, we review other recent examples.

Ridge (stripe or channel) waveguide lasers[18] are typically low-power. Recently, 650 mW with 76% slope efficiency was obtained from an ion-implant Yb waveguide laser[19].

Great progress is occurring in direct-write waveguide lasers[20,21]. Recently, a double-clad direct-write waveguide Nd:YVO4 laser produced 3.8 mJ in pulsed pump operation and 1.5 W continuous-wave[22]. Direct-write Q-switched lasers have been realized through evanescent coupling to graphene[23], carbon nanotubes[24], acetate films[25] and with a co-doped saturable absorber[26].

Another advantage of monolithic lasers is the ability to produce an array of lasers in a single component. Laser diode pump arrays and vertical cavity surface emitting lasers are key examples for semiconductor lasers. A new development is an array of thousands of photonic crystal nanolasers[27]. Recently, a 2 x 2 solid-state multiple component (non-monolithic) laser array was demonstrated[28] with > 0.2 □J energy pulses emitted per laser element. The array could be made monolithic using diffusion bonding composites and mirror coatings.

Microchip monolithic bonded lasers have continued to make progress. Recently, a 1.6 mJ passively Q-switched Yb:YAG thermal bonded composite laser was demonstrated with a 1.5 ns pulse width and 1 MW peak power[29]. In addition, a 2.4 mJ, 2.8 MW peak-power diffusion-bonded composite Nd:YAG/Cr^{4+}:YAG monolithic laser has been proposed[30] for use in automobile engines.

Crystalline waveguide lasers are another viable approach. Under a NASA grant, a laser diode (LD) cladding pumped single-mode 1030 nm laser was recently demonstrated31, in an adhesive-free bonded 40 µm core Yb:YAG crystalline fiber waveguide (CFW) as shown in Figure 3. We achieved a laser output power of 28 W for an input pump power of 44 W at a wavelength of 1.03 µm. The optical to optical efficiency and the slope efficiency are 64% and 78%, respectively.

The laser beam, as the inserted image shown in Figure 4, has a top-hat beam profile with an estimated beam quality of $M_x^2 = 27$ and $M_y^2 = 12$. This laser could be made monolithic with appropriate coatings applied to the crystalline fiber faces.

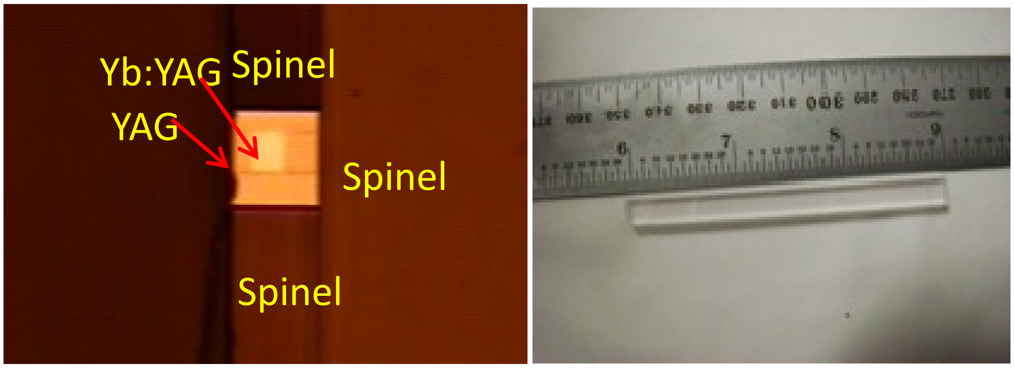


Figure 3. Onyx's prototype single-mode waveguide in 50-µm core crystalline fiber Yb:YAG waveguide laser.

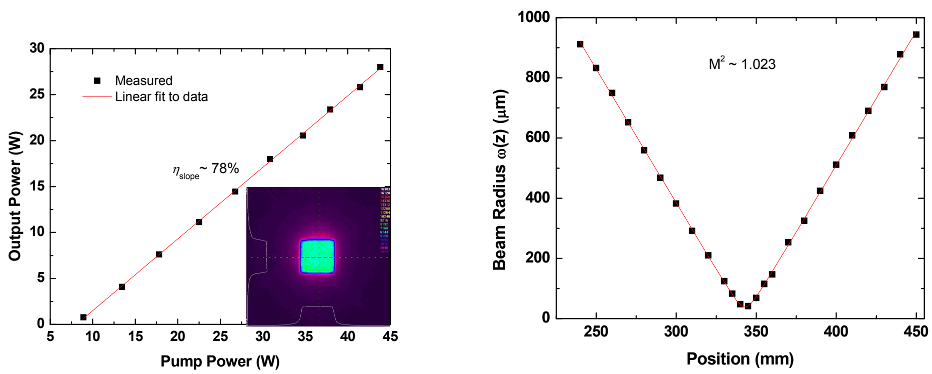


Figure 4. (Left) Laser output power as function of pump power measured in the single-clad CFW. The inserted image is the 2-D beam profile measured by a pyroelectric camera. (Right) Beam radius as a function of position after a 200-mm focus lens.

Planar waveguide monolithic lasers also give impressive high-power results. A near-monolithic thermal-induced planar waveguide laser was demonstrated by Kang et al.[32]. Another near-monolithic approach is a chamfered-edge-pumped planar waveguide Nd:YAG laser that produced 15.5 W at 1064 nm[33]. Ng and MacKenzie demonstrated a 105 W monolithic multimode planar waveguide laser operating at 946 nm in Nd:YAG[34].

Another method for making near-monolithic lasers is to micro-weld[35, 36] individual glass (or possibly crystal) components. For example, a PTR glass VBG can be micro-welded to a doped-glass saturable-absorber[37] that is in turn microwelded to a doped-glass laser medium (Nd, Yb, Er).

To make a viable near-monolithic solid-state laser, a method for direct diode pumping is required. Here we suggest use of a photonic lantern[38] or a multi-mode fiber combiner[39] that is micro-welded to the laser-cavity cladding or the laser cavity. Optical fiber-to-glass welding was recently demonstrated[40] for attaching an endcap to an optical fiber. This micro-welding technique can be used for the integration of the pump-fiber bundle to the laser.

NASA Goddard Space Flight Center is developing a femtosecond direct-write laser capability and plans to explore some of the aforementioned monolithic laser techniques for application to space flight lasers in the near future.

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