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UCRL-CONF-154575

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January 20, 2004

3rd International Symposium on Laser and NLO Materials,
Keystone, CO, July 20-23, 2003

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Abstract

It has recently been reported that several high power, diode-pumped laser systems have been developed based on crystals of Yb:S-FAP [Yb^{3+}:$Sr_5(PO_4)_3F$]. The Mercury Laser, at Lawrence Livermore National Laboratory, is the most prominent system using Yb:S-FAP and is currently producing 23J at 5 Hz in a 15 nsec pulse, based on partial activation of the system. In addition, a regenerative amplifier is being developed at Waseda University in Japan and has produced greater than 12 mJ with high beam quality at 50Hz repetition rate. Q-peak has demonstrated 16 mJ of maximum energy/output pulse in a multi-pass, diode side-pumped amplifier and ELSA in France is implementing Yb:S-FAP in a 985 nm pump for an EDFA, producing 250 mW. Growth of high optical quality crystals of Yb:S-FAP is a challenge due to multiple crystalline defects. However, at this time, a growth process has been developed to produce high quality 3.5 cm diameter Yb:S-FAP crystals and a process is under development for producing 6.5 cm diameter crystals.

PACS: *61.72.-y; 61.50 Ks; 71.55.-i*

Keywords: *B3. Solid State Lasers, A2. Czochralski Method, B1. Oxides, A1. Defects*

Introduction

The development of the apatite crystal and the strontium fluorophosphate derivative has been ongoing for the last 30 years. Initial research was focused on characterizing the calcium fluorapatite for neodymium lasers [1]. More recently, Yb^{3+}-doped materials have been extensively studied by DeLoach, et. al., [1992] [2], for a variety of laser applications due to their useful fundamental properties, Table 1. [2-5] Yb:S-FAP [Yb^{3+}:$Sr_5(PO_4)_3F$] crystals have emerged for laser applications because of its many attractive properties that make it well suited for diode pumping in moderate thermal load applications. The large emission and absorption cross sections (6.0×10^{-20} cm^2 and 10×10^{-20} cm^2, respectively) for nsec pulse extraction, makes diode pumping more cost-feasible for large laser systems due to the reduced requirement on the diode brightness and allows for efficient extraction at moderate fluence. Yb^{3+} doped into S-FAP is pumped at the 900 nm absorption line and with a long, 1.14 millisecond lifetime, allowing for greater energy storage in the material with reduced requirement for diode packages. In addition to the aforementioned characteristics, a high damage threshold (≥ 50 J/cm^2) and low losses (≤ 0.1%/cm) make Yb:S-FAP a suitable material for large laser systems with high repetition rate. Yb:S-FAP is a uniaxial crystal with a refractive index of approximately 1.61 at 1047 nm which is the emission wavelength. The current status of Yb:S-FAP crystal growth and a brief review of the laser systems based on this gain medium will be presented in this article.

Laser architectures based on Yb:S-FAP

The Mercury Laser, at Lawrence Livermore National Laboratory, is the most prominent system that uses Yb:S-FAP as the gain medium (Figure 1). It is a gas-cooled amplifier system intended to yield 100J, 10Hz and 10% efficiency in 3 nsec when completed, in a scalable architecture for inertial fusion energy. Three key technologies are incorporated into the system, specifically, diode pumping to replace flashlamp pumping in previous systems [6,7], active cooling of the amplifier medium with helium flowing over the faces of the slabs, and Yb:S-FAP crystals as the gain medium. The Mercury Laser requires 14 Yb:S-FAP slabs for operation. Each slab has dimensions 4 cm x 6 cm x 0.75 cm in thickness, where the c-axis is oriented along the 6 cm length of the slab. As of the writing of this article, the Mercury Laser is producing 23J at 5 Hz in a 15 nsec pulse, based on partial activation of the system. Single shot operation has yielded 34J and 114W average power operation. The beam quality is M^2=2.8 height and 6.3 width. Future activities involve full activation of the laser with two amplifier heads and 75-100 J of output.

Yb:S-FAP is also being utilized in a diode-pumped high-energy regenerative amplifier targeted as a 1 J, 50-100 Hz, and ≤1 ps [8]. This system is being developed at Waseda University in Japan, in collaboration with Aculight Corporation, as the preamplifier in an all-solid-state laser for laser-Compton X-ray generation. Early experiments have produced greater than 21 mJ at a repetition rate of 50Hz and 17mJ with an input pump energy of 460 mJ and 100Hz repetition rate. Compensation of gain narrowing in the regenerative amplifier is done by reshaping the input pulse spectrum.

Q-Peak, Inc. has demonstrated the first efficient operation of an Yb:S-FAP multipass diode side-pumped, single-stage amplifier. [9] In this configuration, two 900 nm diodes pump a 2 x 8 x 22 mm, 1%-doped, Yb:S-FAP slab, see Figure 2. The total maximum peak pump power from the quasi CW- diodes was 160W with a power intensity of 2.4 kW/cm^2. A maximum slope efficiency of 14% with 16 mJ of energy per output pulse was achieved.

A three-level, continuous-wave Yb:S-FAP laser operating at 985 nm and pumped by a Ti:Sapphire laser, has been reported by Laboratoire Charles Fabry de l'Institut d'Optique in France. [10] The goal of this laser is to provide a potential source to pump an erbium doped fiber amplifier or EDFA that has an output of a few watts and good beam quality. At the time of this article, they had achieved an output power of 250 mW for an incident pump power of 1.45 W at 900 nm from a Ti:Sapphire laser. Small signal gain data corresponded well with the theoretical gain of 2.8 for maximum available pump power.

Growth and fabrication of Yb:S-FAP crystals

The Mercury Laser requires a minimum of 14 Yb:S-FAP slabs for operation. Each slab has dimensions of 4 cm x 6 cm x 0.75 cm in thickness, where the c-axis is oriented along the 6 cm length of the slab. An Yb-doping level of approximately 1.3 x 10^{20} ions/cm^3 is required for the laser. With this requirement, crystal growth becomes challenging because only ~12% of Yb in the initial melt is incorporated into the S-FAP lattice creating instabilities at the growth interface. A significant effort has been put forth to understand the nature of the defect chemistry in Yb:S-FAP crystals and to develop a growth process to yield crystals from which slabs can be fabricated. [11]

Crystal growth:

High optical quality crystals of Yb:S-FAP are grown by using the Czochralski method in a high temperature oxide-type furnace at a melting temperature of approximately 1786°C. Iridium crucibles are used at this high temperature and to prevent reaction with the melt during growth. The crystals are grown from seeds oriented along the [001] direction. Rotation rates of approximately 10-15 rpm have been effective for boule diameters up to 3.5 cm and a pull rate of 0.5 millimeter per hour is typically used to reduce defect formation. Boules of dimension 3.5 cm diameter by 12 cm in length are routinely grown with good optical quality, Figure 3.

Defects:

There are six possible defects that can arise in Yb:S-FAP crystals including; cloudiness, bubbles in the core region, anomalous absorption, cracking, low-angle grain boundaries, and inclusions at the outer surface of the boule. However, a growth procedure has been developed to control or eliminate each of the defects. An excess of SrF_2 in the melt has been effective in controlling, and most times eliminating, the cloudiness in Yb:S-FAP crystals. The cloudiness has been attributed to second phase precipitation on line defects in the crystal lattice. Growth along the c-axis and axial thermal gradients of <60°C/cm above the melt, are critical for eliminating the anomalous absorption that occurs as a broad band from approximately 925-1000 nm with the largest peak at 975 nm. Low-angle grain boundaries have been eliminated by growing "seed extensions" and choosing a small cone angle to maintain a stable growth interface. Grain boundaries appear as slight shifts in the refractive index or waves running through the crystal in sheets oriented perpendicular to the c-axis. Crystals of Yb:S-FAP are grown in a high thermal gradient furnace to stabilize the growth interface and control the formation of bubble core defects. The bubble core is attributed to constitutional supercooling where a supercooled liquid is formed from concentration gradients of rejected melt components pushed along in front of the advancing interface. Second phase inclusions consisting of ytterbium oxide crystallites can be pushed to within 1 mm of the skin of the boule by lowering the Yb-doping level and maintaining a higher axial thermal gradient above the melt as for the core defects. Cracking is also an issue and is controlled by narrowing the diameter of the crystal at the end of growth and not separating it from the melt during the cooling process. This method utilizes the large thermal load of the melt to conduct heat into the crystal and reduce thermal gradients. Also, a significant reduction of defects that cause strain in the crystals has significantly reduced cracking.

Fabrication:

Cracking has also been a major issue during the fabrication of Yb:S-FAP slabs for the Mercury laser. Specifically, cutting of the crystals has been plagued by cracks that propagate perpendicular to the length of the crystal. This type of cracking has also been an issue during fabrication into half slabs for bonding at Onyx Optics. In an effort to understand the internal stress in the crystals that results in the cracking, UC Davis performed experiments and calculations that identified the axial stress in the crystals to be as high as 50 MPa at the center with a parabolic stress field. As a result, alternative cutting techniques were developed using a water jet to minimize heating during the cutting process. This technique has proven to be 100% successful in eliminating cracking during the cutting process.

Half size crystals from 3.5 centimeter diameter boules, are diffusion bonded at Onyx Optics to form full size slabs for the Mercury laser. At this time, seven slabs have been activated in the laser and seven additional slabs are in process for activation of the full size Mercury system.

Scaling Growth:

Other growth directives have included scaling the size of Yb:S-FAP crystals to >7cm diameter. The first large diameter crystals are being grown at Northrop Grumman/Space Technologies, yielding 6.5 cm diameter boules that have the possibility of yielding 2 full size amplifier slabs (Figure 4). The current issues with the larger diameter crystals are an approximate 3 cm bubble core, grain boundaries, and cracking from thermal stress and defects. However, at this time, a number of crystals have been grown and the first full size 4 x 6 x 0.75 cm slab has been harvested.

Summary

Yb:S-FAP crystals are most desirable for applications requiring high energy with a moderate repetition rate. A sufficient understanding of growth parameters has been achieved to manage or eliminate each of the defects so that large, high optical quality crystals can be routinely grown. Cracking during fabrication has been solved by employing a water jet technique to cut the crystals without heating. Recently, various table-top laser systems have been built by ELSA, FESTA, and Q-Peak, using Yb:S-FAP as the gain medium. Finally, Yb:S-FAP has been developed for the Mercury laser which is now producing 34 J in a nanosecond pulse and 23 J at 5 Hz.

Acknowledgements

The authors would especially like to thank Camille Bibeau and Jay Dawson for overseeing the development of diffusion bonding to permit the growth of half-slabs (in conjunction with Onyx Optics), and for establishing algorithms to assess optical quality. In addition, we wish to acknowledge Northrop-Grumman, Poly-Scientific (Synoptics Division) for their collaborative efforts in growing Yb:S-FAP crystals on a contract with LLNL and providing useful material and discussions. Peter Thelin deserves great thanks for his tireless efforts in devising unique methods for cutting and polishing these extremely fragile crystals. Mike Hill, Jon Rankin, and Adrian DeWald from UC Davis did excellent work in determining the internal stress in the crystals which was crucial in determining the correct cutting method to prevent cracking. Finally, the authors are indebted to Steve Payne for his invaluable insights and discussions throughout this work.

*Work done under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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Figure Captions:

Figure 1. Picture showing the Mercury Laser architecture.

Figure 2. Schematic of the multi-pass side-pumped Yb:S-FAP amplifier designed by Q-Peak.

Figure 3. High optical quality Yb:S-FAP boules produced by controlling each of the defects.

Figure 4. Large, 6.5 cm diameter crystals are being developed to produce full size amplifier slabs for the Mercury laser.

Table 1. Comparison of some of the fundamental properties of Yb-doped materials.

	Yb:S-FAP	Yb:YAG	Yb:SiO_2	Yb:KGW
` Pump wavelength (nm)	**900**	**941**	**915**	**981**
Laser wavelength (nm)	**1047**	**1030**	**1039-1062**	**1025-1045**
Fluorescence lifetime (ms)	**1.14**	**0.95**	**0.94**	**0.6**
Absorption cross section ($10^{-20}cm^2$)	**9.0**	**0.7**	**0.4**	**12**
Emission cross section ($10^{-20}cm^2$)	**6.0**	**1.9**	**0.4**	**2.8**
Saturation fluence (J/cm^2)	**3.1**	**9.6**	**44**	**6.9**
Pump saturation intensity (kW/cm^2)	**2.9**	**28**	**47**	**12**
Spectral bandwidth (nm)	**5**	**10**	**200**	**20**
Thermal conductivity (W/mK)	**2**	**10**	**0.6**	**2.6-3.8**
Laser Geometry	**Slabs/rods**	**Thin disk/rods**	**Fibers**	**Thin disk/rods**

Figure 1.

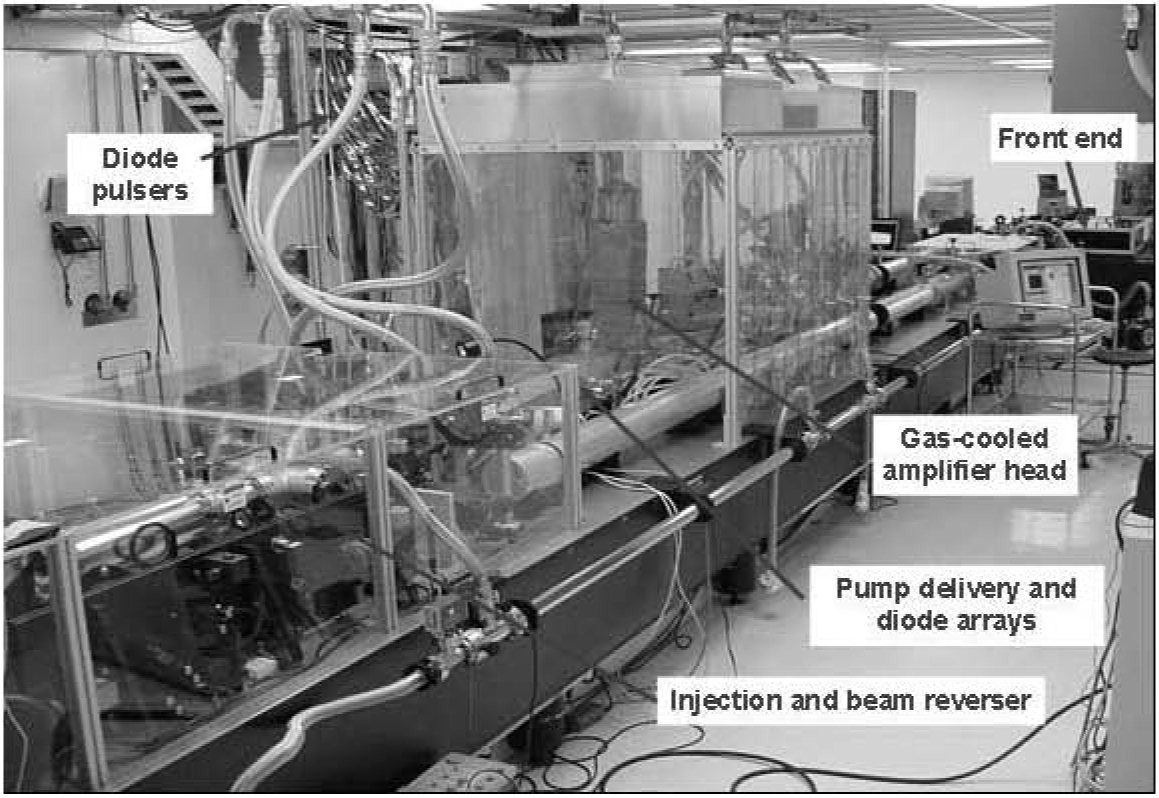
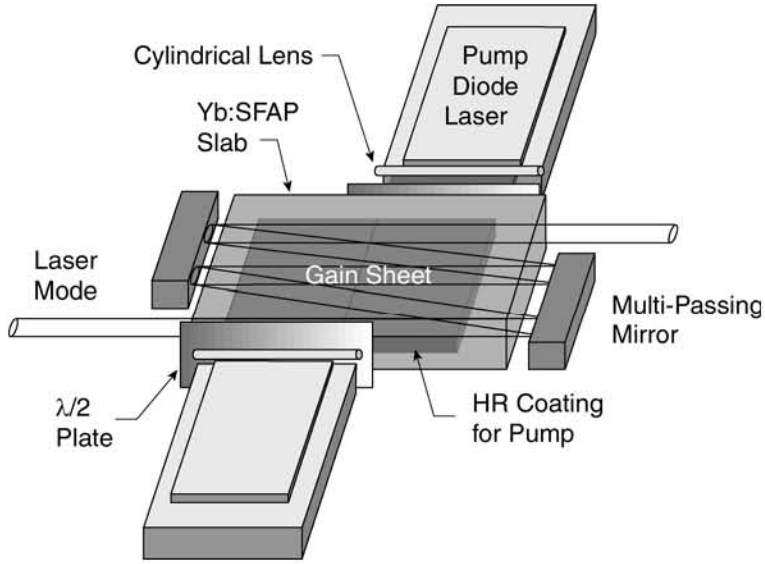
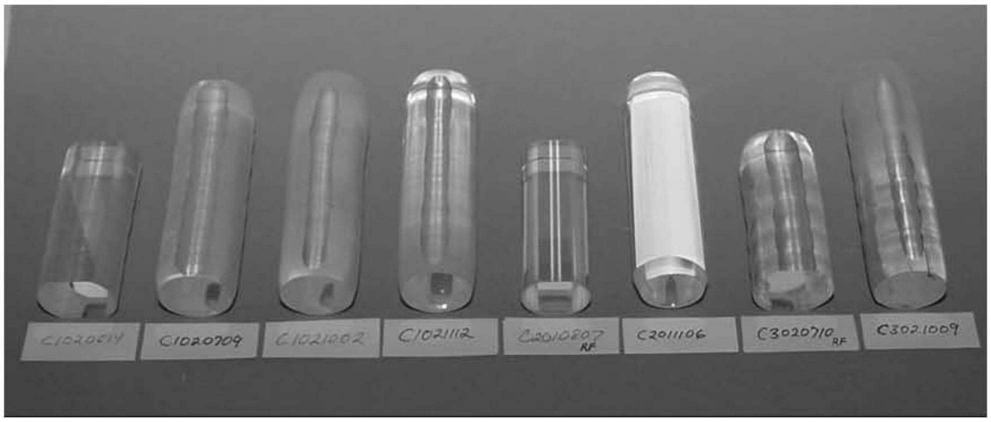

Diode pulsers
Front end
Gas-cooled amplifier head
Pump delivery and diode arrays
Injection and beam reverser

Figure 2.



Cylindrical Lens
Pump
Diode
Laser
Yb:SFAP
Slab
Laser
Mode
Gain Sheet
Multi-Passing
Mirror
λ/2
Plate
HR Coating
for Pump

Figure 3.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C2011106
C3020710 RF
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Figure 4