High Power Operation of Cryogenic Yb:YAG

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• Early work on cryogenic lasers
• MPS laser technology
• Recent program on high-power cryogenic Yb:YAG
Early Cryogenic Laser Technology
Reasons for Cryogenic Cooling of Solid State Lasers

• **Thermal**
  - Increased thermal conductivity of host crystal at low temperatures
    - Reduced heat rise inside crystal, reduced thermal gradient
    - Reduced stress, allowing higher power output/unit volume
      - Reduced thermo-optic distortion in crystal

• **Spectroscopic**
  - Reduced population in lower level for 3½-level lasers
  - Increased upper-laser-level lifetime for laser transitions that are thermally quenched
  - Stability of laser-active ion (for color-center lasers)

3,339,150
LIQUID COOLED SOLID STATE LASER
Colin Bowness, Weston, Mass., assignor to Raytheon
Company, Lexington, Mass., a corporation of Delaware
Filed June 3, 1963, Ser. No. 284,933
3 Claims. (Cl. 331—94.5)
United States Patent

McMahon

COLDING SYSTEM FOR LASING MEDIA

Inventor: Donald H. McMahon, Carlisle, Mass.
Assignee: Sperry Rand Corporation
Filed: Oct. 13, 1969

Appl. No.: 865,910

U.S. Cl. 331/94.5, 165/185
Int. Cl. H01S 3/04, F28t 7/00
Field of Search 331/94.5

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3,471,801 10/1969 Woodbury et al. 331/94.5
3,361,989 1/1968 Siron 331/94.5
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OTHER PUBLICATIONS


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Abstract

Heat generated within a lasing medium operating in a laser pumping cavity is efficiently removed from the pumping cavity by use of a heat sink located exterior of the cavity. A tube formed of a single crystal of sapphire surrounds the laser medium and extends through an end wall of the pumping cavity. There, the sapphire tube is in turn surrounded by a metal heat exchanger element that may be operated at cryogenic temperatures. Undesired condensation is prevented from forming adjacent the laser medium by forming the pumping cavity as a sealed chamber and evacuating it to a relatively low gas pressure.

2 Claims, 3 Drawing Figures
McMahon apparatus
First Broadly Tunable Lasers were Cryo-Cooled (1963)

**OPTICAL MASER OSCILLATION FROM Ni²⁺ IN MgF₂ INVOLVING SIMULTANEOUS EMISSION OF PHONONS**

L. F. Johnson, R. E. Dietz, and H. J. Guggenheim
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 29 August 1963)

**Phonon-Terminated Optical Masers**

L. F. Johnson, H. J. Guggenheim, and R. A. Thomas
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 11 April 1966)

The characteristics of phonon-terminated coherent oscillation associated with Ni²⁺, Co²⁺, and V²⁺ ions in rutile and perovskite fluorides are described. Continuous tunability over portions of the vibronic continuum of Ni²⁺ in MgF₂ has been demonstrated. The system has been thermally tuned in discontinuous segments over a total wavelength span from 1.62 to 1.80 μ, the longest continuous segment being 250 Å (82 cm⁻¹). Alternatively, a frequency-selective element (prism) has been used to vary the oscillation frequency (at a fixed temperature of 85°K) in discontinuous segments between 1.62 and 1.84 μ. The discontinuities are a consequence of structure present in the vibronic continuum of Ni²⁺ in MgF₂. Continuous-wave oscillation has been obtained from Ni²⁺ ions in MgF₂ and MnF₂, requiring, respectively, less than 65 and 240 W of power into a tungsten lamp. Both systems display continuous spiking, and the spectral distributions of maser emission may be very complex.
A Compact Efficient Liquid Nitrogen System for Cooling Solid State Lasers: Application to YAG: Nd$^{3+}$ and ABC-YAG$^*$

J. Doehler and S. A. Solin

The Department of Physics and The James Franck Institute, The University of Chicago, Chicago, Illinois 60637

(Received 6 April 1972; and in final form, 5 May 1972)

A recirculating liquid nitrogen cooling system for optically pumped solid state lasers is described. It has been used to obtain cw emission from YAG: Nd$^{3+}$ and ABC-YAG at 1.06 and 2.09 μm, respectively. The system is versatile and can easily accommodate intercavity components such as an acoustic Q-switch or a Brewster window. With 3 kW electrical input to a pair of tungsten iodine pump lamps coupled to either YAG: Nd$^{3+}$ or ABC-YAG by a double elliptical cavity, the measured liquid nitrogen consumption was ~3.3 cm$^3$/sec at a flow rate of 37 cm$^3$/sec.
Ho laser with 50-W output and 6.5% slope efficiency

R. Beck and K. Gürs

Battelle Institut, e.V., Frankfurt/Main, West Germany
(Received 7 July 1975)

We report the observation of continuous high-power laser emission from sensitized YAG. The crystal was immersed in flowing liquid oxygen precooled to 77 K. With a linear tungsten-halogen lamp in a single-ellipse pumping configuration an output power of 50 W with a 6.5% slope efficiency was obtained.

PACS numbers: 42.60.G, 87.60.C

Work on Cryogenic Lasers Extends Back to 1978

Publications (at MIT/LL)


Products (at Schwartz Electro-Optics, now Q-Peak)

CW Co:MgF$_2$ lasers (5 W power) built and shipped to Northwestern University and White Sands Missile Range, NM (circa 1990)
Average Power Levels in the 7-10 W range were Obtained, Limited by the Pump Source

Pulsed Ni:MgF₂ laser pumped by Nd:YAP laser at 1.34 um (MIT LL Solid State Research 1982:1)

Both lasers operated in the TEM₀₀ mode, because of the high thermal conductivity of the laser crystals at liquid nitrogen temperature
Photos of Cryogenic Lasers at MIT/LL (1978-1985)
Yb:YAG Cryogenic Laser Technology
Diode Pumps have Enabled Yb:YAG lasers

Energy levels in Yb:YAG

\[
\begin{align*}
\text{2F}_{5/2} & \quad 10679 \text{ cm}^{-1} \\
\text{2F}_{7/2} & \quad 10624 \\
\text{2F}_{7/2} & \quad 10327 \\
\text{Energy} & \quad 968 \text{ nm} \\
941 \text{ nm} & \quad 1030 \text{ nm} \\
785 & \quad 612 \\
565 & \quad 0
\end{align*}
\]

Yb:YAG absorption spectrum, 77 and 300 K

Absorption Coefficient (cm\(^{-1}\))

Laser Wavelength
Distortion (OPD)  

\[
FOM_d = \kappa / [\eta_h |dn/dT|]
\]

Depolarization  

\[
FOM_b = \kappa / \eta_h |\alpha|
\]

\(\eta_h\) \equiv \text{fractional thermal load}  
\(\kappa\) \equiv \text{thermal conductivity}  
\(\alpha\) \equiv \text{thermal expansion}  
\(dn/dT\) \equiv \text{change in refractive index with temperature}

- Larger material FOM’s give less distortion, stress-induced birefringence
- Key material properties \((\kappa, \alpha, dn/dT)\) expected to scale favorably at lower temperature in bulk single crystals
- \(FOM_b\) is irrelevant in birefringent media since there will be no depolarization (unless propagating down optical axis)
- Assumes equal laser efficiency

Courtesy: T.Y. Fan, MIT/LL
Cryo-cooled Yb:YAG has Greatly Enhanced Potential High-Power Performance

- \( \text{FOM}_b \) and \( \text{FOM}_d \) >30X larger in 100 K Yb:YAG compared with 300 K Nd:YAG
  - ~ >12X larger than 300 K Yb:YAG (assuming equal optical efficiencies)
- Broad absorption band maintained at low temperature
  - Sharpening of absorption features at low temperature does not drive pump wavelength control requirements

Courtesy: T.Y. Fan, MIT/LL
• Breadboard features
  – Yb:YAG cryogenically cooled in LN₂ cryostat
  – Efficient end-pumping with high-brightness diode pump lasers
  – Yb:YAG crystal indium soldered to copper mount for heat-sinking
  – Large beam radius (~ 1 mm) resonator to avoid optical damage
MIT/LL has Shown Steady Progression of Power

Proof-of-principle demonstration at MIT LL in 1997
300 W: Ripin et al., IEEE JQE, v 41, 2174 (2005)

MIT now planning to build cryo Yb:YAG modules for possible insertion into ABL
The Promise of Cryogenic Solid-State Lasers

David C. Brown, Member, IEEE

(Invited Paper)

Abstract—Cryogenic cooling of solid-state lasers has a number of important benefits, including the near vanishing of optical distortion in high average power lasers, as well as enhanced spectroscopic and lasing properties. These benefits are just beginning to be exploited to produce compact high average power lasers whose output is scalable, near diffraction limited, and whose efficiencies will exceed those of modern bulk solid-state lasers. In this paper, we review the history of cryogenically cooled solid-state lasers and the benefits of cryogenic cooling, including optical and laser properties and thermal and thermooptic properties; examine cryogenic amplifiers and cooling methods, including a straight-through propagation thin-disk configuration that does not perform well at room temperature, and summarize the experimental performance demonstrated to date. As a specific example, we examine the spectroscopic and lasing properties of Yb:YAG and show that compact high efficiency and high average power, near diffraction limited lasers (> 100 kW) can be realized in the near future using presently available technology.

Index Terms—Cryogenic laser, diode-pumped laser, solid-state laser, Yb:YAG laser.
Q-Peak’s Approach to Cryogenically Cooled Yb:YAG Lasers
Q-Peak’s MPS DPSSL Design Obtains High Efficiency, High Beam Quality with Side-Pumping


“Gain Module”
MPS Nd:YLF CW oscillator performance scales with pump lasers

- 40 W, MM
- 30 W, TEMoo
- 20 W, TEMoo

$M^2 = 1.05$
Goals of Newest Cryo Laser Program at Q-Peak

• Design a *side-pumped* breadboard 250-W Q-switched Yb:YAG laser, with the capability of cooling to cryogenic temperatures.

• Construct the 250-W Yb:YAG laser and measure the multimode, multi-passing, and repetitively Q-switched performance, at cryogenic temperatures.

• Achieve a goal for the laser beam quality of $M^2 \leq 2$ and a goal for the Q-switch repetition rate of 5 kHz without optical damage.

Program funded by AFRL Phase II Contract # FA9451-04-C-0151
Cryo Yb:YAG crystal is a 4-mm-thick slab

- Crystal is 2% doped and 28 x 10 x 4 mm in size.
- Two pump diode laser arrays are offset on the opposite sides of the slab.
- Heat is removed from the two large faces of the crystal.
Model thermal distribution in Yb:YAG crystal

The maximum temperature occurs at the pump faces and is $25^\circ$ higher than the faces in contact with the heat sinks.
Crystal Mount Achieves Effective Cooling
Sectional View of Model Temperature Distribution

- Temperature of the center of the crystal is ~ 129 °K.
- Crystal surface-temperatures at the interfaces of the base and clamp plates are 90 °K and 101 °K respectively.
- Heat removal from the crystal mount is only from the base plate.

Assumptions:
- Bottom surface at 100 K
- Uniform heat deposition of 360 W in the crystal.
- Perfect contact between the crystal and heat sinks. Also, perfect contact between the base and clamp plates.
Calculated Beam Sizes of Cavity

- Assumes weak thermal lensing
- Stable, but very sensitive to mirror misalignment
Nuvonyx Diode Arrays are High-Power Side Pumps
Pump Focusing Design Uses Simple Optics
Pump Beam at Crystal Face

- Imaged at the plane of crystal surface
- Intensity of the beam was reduced by operating the laser in pulse mode
- Beam size 10 X 2 mm
- CCD camera and Spiricon beam analyzer.
Experimental Setup of Cryo System uses Large Dewar for long run times
- The laser was multi-mode in the horizontal plane and nearly diffraction limited in the vertical plane.
- 98% of pump power was incident on the crystal and 98% was absorbed.
High-efficiency Multimode Lasing is Obtained

- Maximum output power was 400 W with a total pump power of 720 W.
- With 80%-reflective output coupler, the slope efficiency was 62% and optical-to-optical efficiency was 56%.
Measured Temperatures at Crystal Base and Clamp Plates Show Heat Load Lasing, Non-Lasing

Compared with the lasing condition, in the non-lasing condition, the temperatures of the clamp and base plates were 26 °K and 11 °K higher respectively.
• Thermal wedging due to the temperature difference between the top and bottom of the crystal.
• Camera was 1 m away from the crystal.
• Beam deflection is prominent in the vertical plane
• Calculated thermal wedging in the vertical plane is ~ 0.7 mrad
Preliminary 5-Pass Measurements

- We are still working on optimizing the cavity design
The laser was QCW pumped at 25% duty cycle.
The laser was QCW pumped at 50% duty cycle.
• Continuous LN$_2$ pumping through the base and clamp plate of the crystal.
• Fiber coupled sources are available in a variety of configurations
• Up to 750 W in a 400 um core fiber (NA = 0.22), with further improvements in power expected in the future
End-pumped Cryo Yb:YAG could be Seed Oscillator for High-Power System


Drawing courtesy: T.Y. Fan, MIT/LL
Q-switched Cryo Yb:YAG Estimates

Pulsewidths from 5-60 ns are Possible at 5-kHz Pulse Rates

Average Powers from Cryo Yb:YAG Depend on Achievable Mode Size
Conclusions

• Q-Peak has returned to the development of cryogenic laser technology, following on the recent efforts at MIT Lincoln Laboratory with Yb:YAG systems

• We have demonstrated a 400 W, cw, cryogenically cooled Yb:YAG laser.

• We obtained a slope efficiency of 62% and optical-to-optical efficiency of 56% in a side-pumped slab geometry, in good agreement with our estimates.

• The laser is multi mode in the horizontal plane and nearly diffraction limited in the vertical plane.

• Beam quality will be improved by multi passing the laser in the crystal – experiments underway, along with Q-switching.