Solid-State Optical Cryocoolers

Richard Epstein, ThermoDynamic Films, LLC
Mansoor Sheik-Bahae, University of New Mexico
Markus Hehlen, Los Alamos National Laboratory

Optical cryocooling is the coolest solid-state refrigerator

Has advantages over other cryocoolers

Almost ready for “real-world” applications.
Ytterbium-based Laser Cooling

- **Anti-Stokes Fluorescence**

  Lower energy photons enter the solid and excite dopant ytterbium atoms.

  Excited ytterbium atoms absorb energy from the solid and emit higher energy photons. **This creates cooling.**

Cooling Cycle

1) Atoms are excited from the top of ground state to the bottom of excited state by the laser

2) Excited atoms absorb phonons to reach thermal equilibrium with lattice host

3) Spontaneous fluorescence at a greater photon energy ($h\nu_f > h\nu$) brings atoms back to ground state

4) Ground state atoms absorb phonons to thermalize

**Ideal cooling efficiency:**

$$\eta_c = \frac{h\nu_f - h\nu}{h\nu} = \frac{\lambda}{\lambda_f} - 1$$
Fighting Background Absorption

\[ \eta_c \quad ; \quad \eta_{\text{abs}} \frac{h \nu_f}{h \nu} - 1 > 0 \text{ for cooling} \]

\[ \eta_{\text{abs}} = \frac{\alpha_r(\nu)}{\alpha_r(\nu) + \alpha_b} = \frac{1}{1 + \frac{\alpha_b}{\alpha_r(\nu)}} \]

Competition between resonant absorption \( \alpha_r \)
And parasitic background absorption \( \alpha_b \)

Resonant absorption:
Converts \(~ 1\%\) of absorbed laser power into cooling heat lift

Background absorption:
Converts 100\% of absorbed power into heat
Lower and Lower Temperatures

- 77 K (LN₂)
- 123K (NIST)
- 93 K

**TEC Devices**

- Yb:ZBLAN (1%)
- Yb:YLF (5%)
- Yb:YLF (10%)
Best Cooling Material To Date

Plot of $\eta_C$ for a Yb:YLF crystal
Yb doping = 10% wt.
Background absorption: $\alpha_b = 2.0 \times 10^{-4}$ cm$^{-1}$

Cooling measurements with 54 W laser tuned to 1020 nm
Origin of Background Absorption? 
Iron May be the Main Problem
Paths to Lower Temperatures

Iron may be removed by
Chelation Assisted Solvent Extraction or by
Electrochemical Purification
Paths to Higher Efficiencies

Lower pump energies allow higher efficiencies

Photon energy shift is limited by thermal excitations

$$\eta_c \sim \frac{\hbar \nu_f}{\hbar \nu} - 1 \sim \frac{kT}{\hbar \nu}$$

Choose Active Ions and Crystal Hosts

<table>
<thead>
<tr>
<th>Dopant Ion</th>
<th>Pump Energy</th>
<th>Cooling Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yb$^{3+}$</td>
<td>1.21 eV</td>
<td>$\sim$1.5%</td>
</tr>
<tr>
<td>Tm$^{3+}$</td>
<td>0.62 eV</td>
<td>$\sim$2.9%</td>
</tr>
<tr>
<td>Dy$^{3+}$</td>
<td>0.37 eV</td>
<td>$\sim$4.9%</td>
</tr>
</tbody>
</table>
Multidisciplinary Challenges

Material Science
- Host/ion ($E_f, E_p, \alpha, W_{nr}, W_r$)
- Material purity ($W_{nr}, \alpha_b$)
- Concentration ($\alpha, W_{nr}$)
- Sample preparation ($W_{nr}, \alpha_b$)

Laser Cooled Device

Optical Engineering
- Optical cavity design ($\alpha L, \eta_{ext}$)
- Pump laser ($\lambda_p, I$)

Thermal Engineering
- Choice of payload ($P_{pay}, T$)
- Thermal link ($P_{pay}, P_{int}$)
- Intrinsic heat loads ($P_{int}$)
Roadmap for High-Efficiency RE-Based Optical Cryocoolers

Additionally – there have been major breakthroughs in cooling semiconductors by Prof. Qihua Xiong’s group from Nanyang Technological Univ. in Singapore
Advantages Optical Cryocoolers

- **Solid-State**
  - No vibrations
  - Reliable – no moving parts

- **Compact and low mass**

- **Novel thermal management**
  - Pump laser can be far from cooler head
  - Waste fluorescence can be radiated away or recycled into electrical power

- **No EMI**

- **Insensitive to strong magnetic fields**
Initial Uses for Optical Cryocoolers

Ultra-stable frequency standards

no vibrations, $T_{\text{cooler}} \sim 124K$

Infrared cameras (space-based and terrestrial)

no vibrations, compact, reliable, $T_{\text{cooler}} < 150K$

Germanium-based gamma-ray spectrometers

no vibrations, $T_{\text{cooler}} < 120K$

Electron microscopes

no vibrations, $T_{\text{cooler}} \sim 160K$

Low-noise amplifiers for antennas

low mass, $T_{\text{cooler}} < 120K$
Ultrastable Laser Cavity Frequency Standard

A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity


Requires vibration-free cooling at 124 K

Collaboration with Prof. Jun Ye (NIST)
Cryocoolers for IR cameras on satellites should produce very little vibration and be extremely reliable.

MTI multi-thermal image of SF Bay
Optical Cryocoolers can Decrease Mission Weight

Lowest Mass for Space-Borne Coolers (including solar panels etc.)

Adapted from a study by Ball Aerospace & Technologies Corp.
Gamma-Ray Spectroscopy

High-Purity Gamma Ray Spectrometers have extremely high energy resolution at T<120K

But – the spectra are severely degraded by *vibrations and microphonics*.

**Solid-state cryocooling could enable portable, high-energy-resolution gamma-ray spectrometers.**
The Essential Parts of an Optical Cryocooler

- Cooling Crystal
- Laser light
- Heat-sunk chamber - absorbs the waste fluorescence
- Cold finger
- Sapphire thermal link

Heat-sunk chamber - absorbs the waste fluorescence
Very Little Cold Material

Rapid cool-down and low inertial

Total cold mass \(\sim 10\) g

- Cooling Crystal
- Thermal Link
- Chamber at \(\sim 300\) K
Building a General Prototype

- Mechanical support
- Cold finger
- Cooling crystal
- Heat removal chamber
- Thermal link
- Laser optics
Summing-up

Optical cryocooling can now achieve sub-100 K temperatures, and there are strategies for getting below LN2

Advantages: Solid-state cooling, no moving parts, no vibrations, low mass and compact.

Applications: Laser metrology
IR detectors:
Gamma-ray spectrometry
Cold electronics.

If you have other ideas, let’s talk!
Team

Prof. Mansoor Sheik-Bahae\textsuperscript{2},
Dr. Markus Hehlen\textsuperscript{5}
Dr. Seth Melgaard\textsuperscript{2,3},
Dr. Denis Seletskiy\textsuperscript{4},
Dr. Alex Albrecht\textsuperscript{2};
Mohamed Ghasemkhani\textsuperscript{2}

R. E. \textsuperscript{1}

\textsuperscript{1}ThermoDynamic Films LLC, Santa Fe, NM
\textsuperscript{2}Univ. New Mexico, Dept. Phys. & Astron., Albuquerque, NM
\textsuperscript{3}USAF, Res. Lab., Space Vehicles Directorate, Kirtland AFB, NM
\textsuperscript{4}Univ. Konstanz, 78457 Konstanz, Germany
\textsuperscript{5}Los Alamos National Laboratory, Los Alamos, NM

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e-mail me if you want some review papers
Richard Epstein, ThermoDynamic Films LLC, richard.epstein@gmail.com