Modeling thermal parasitic load lines for an optical refrigerator

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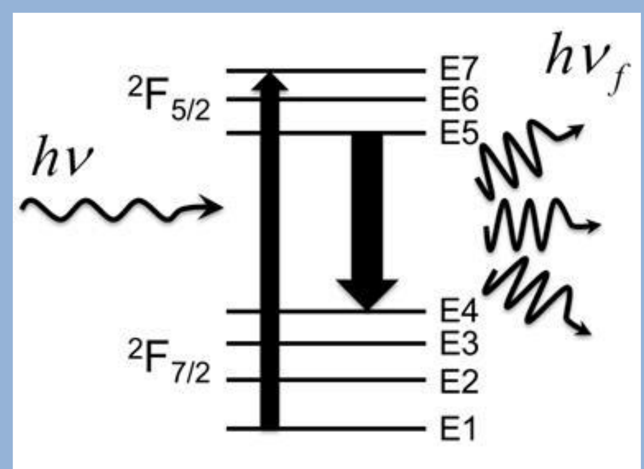
Abstract

Optical refrigeration is currently the only completely solid state cooling method capable of reaching cryogenic temperatures from room temperature. Optical cooling utilizing Yb:YLF as the refrigerant crystal has resulted in temperatures lower than 123K measured via a fluorescence thermometry technique. However, to be useful as a refrigerator this cooling crystal must be attached to a sensor or other payload. The phenomenology behind laser cooling, known as anti-Stokes fluorescence, has a relatively low efficiency which makes the system level optimization and limitation of parasitic losses imperative. We propose and model a variety of potential designs for a final optical refrigerator, enclosure and thermal link; calculate conductive and radiative losses, and estimate direct fluorescence reabsorption. We generate parasitic load-lines; these curves define temperature-dependent minimum heat lift thresholds that must be achieved to generate cooling for an eventual detector.

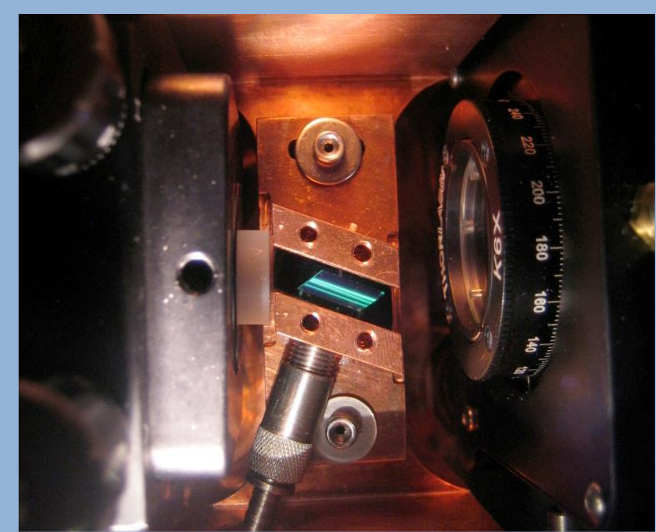
Optical Refrigeration

- How it works: Absorption of laser light promotes an electron from the ground state to the excited state manifold. The atom thermalizes, spontaneously emits at a frequency $\nu_f > \nu$. The atom thermalizes to the E4 energy level and repeats.



- Cooling efficiency of an optical refrigerator crystal (not system efficiency):

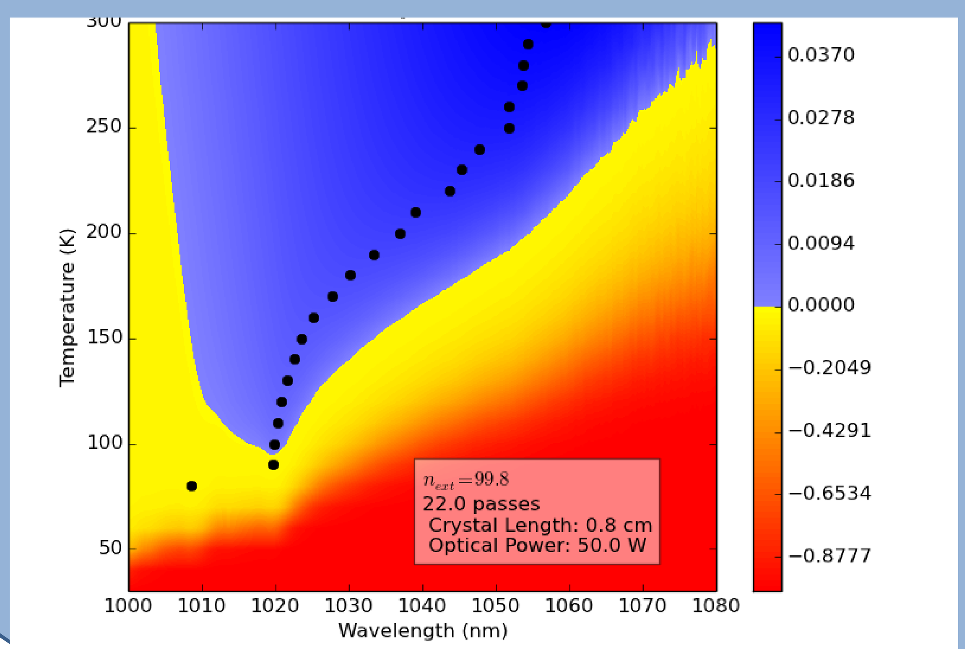
$$\eta_{cool} = \eta_{ext}\left[\frac{1}{1+\alpha_b/\alpha(\lambda,T)}\right]\frac{\lambda}{\lambda_f(T)} - 1$$

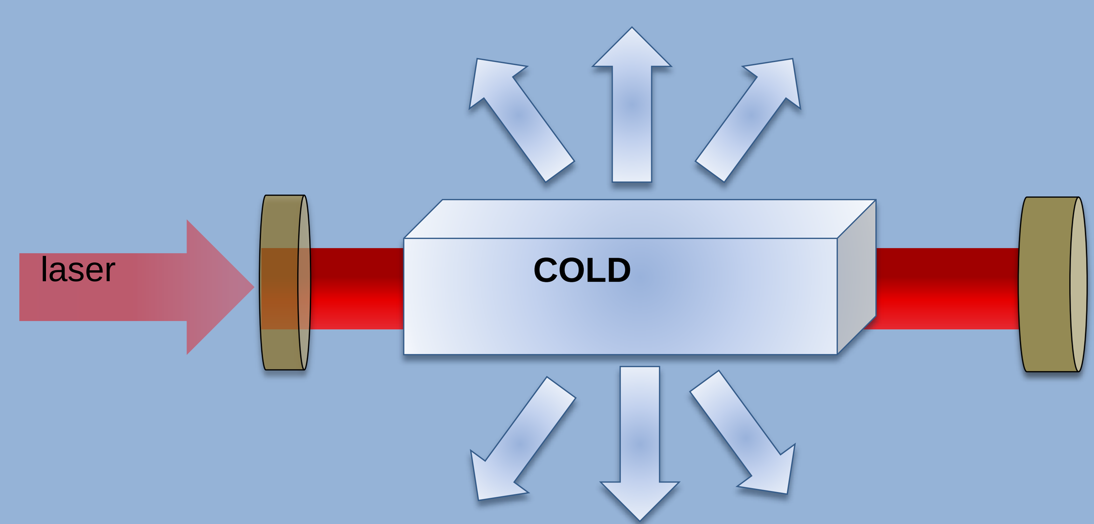


Optical refrigerator experiment at the University of New Mexico

Melgaard, S.D., Albrect, A., Hehlan M. P. ,Seletskiy, D.V., and M., Sheik-Bahae, M., *Optical refrigeration cools below 100 K.* IEEE Lasers and Electro-Optics CLEO (2014)

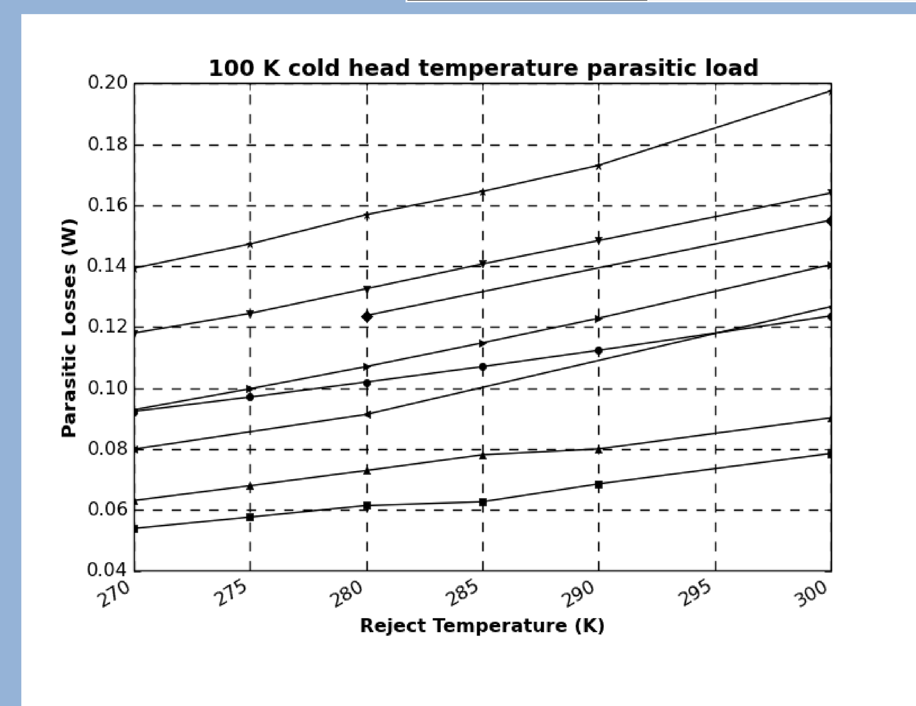
Minimum Achievable Temperature (MAT) map

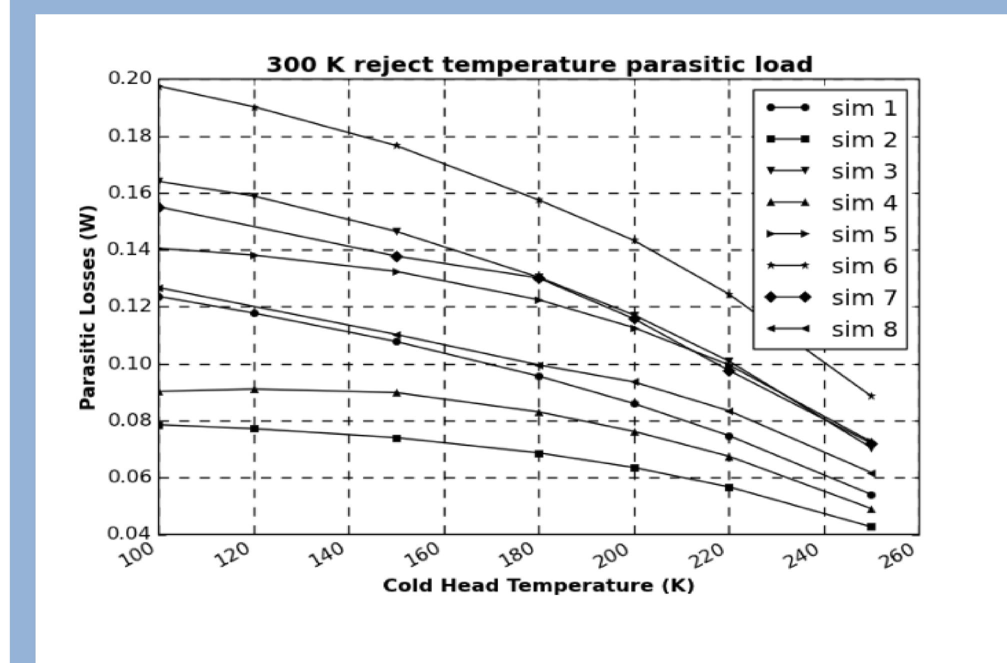




Results

Simulation	Support	Link Geometry	Enclosure Geometry
1	Aerogel	L-link	Tight
2	Kevlar	L-link	Tight
3	Aerogel	Tetris-link	Tight
4	Kevlar	Tetris-link	Tight
5	Kevlar	Tetris-link	Acktar Cube
6	Aerogel	Tetris-link	Acktar Cube
7	Aerogel	L-link	Acktar Cube
8	Kevlar	L-link	Acktar Cube



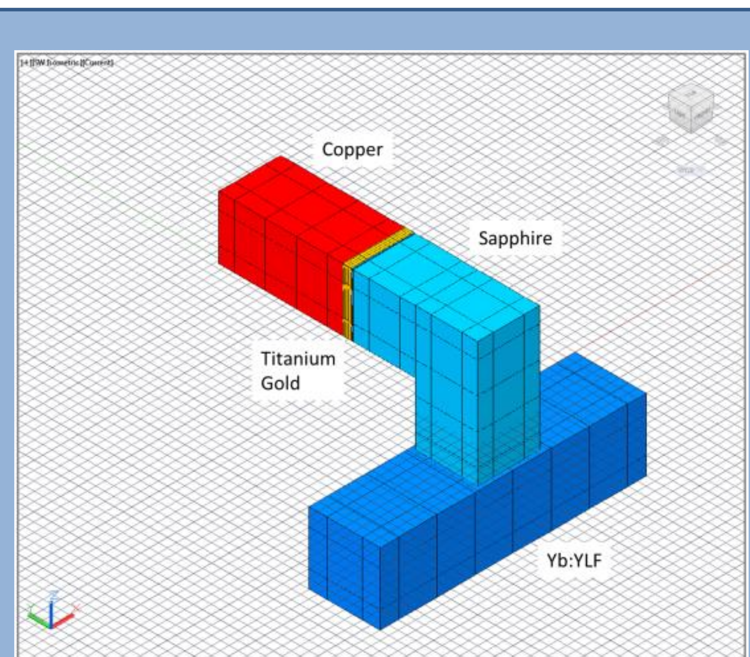


Conclusions

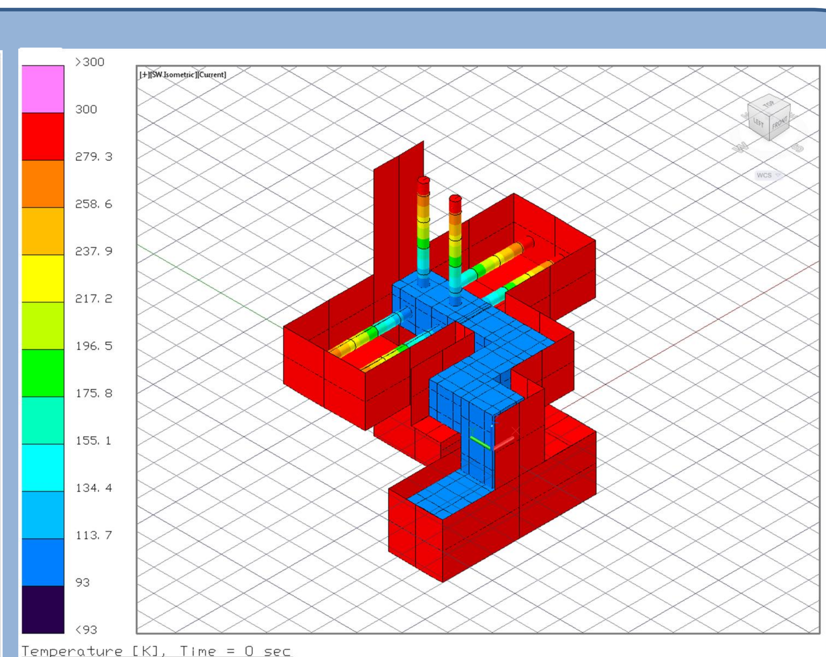
- Kevlar Cat's cradle suspension best minimizes conductive losses.
- An Aerogel support could not be completely eliminated
- The "L" link supported with a Kevlar cat's cradle system in a tight enclosure best minimized the radiative and conductive losses.
- A reduction of reject temperature from 300K to 271 K at 93 K cold tip temperature accounts for additional losses of between 25 and 60 mW. This could help UNM estimate their parasitic losses.
- A prototype design with a simple "L" link with Kevlar support and larger, properly heat sunk enclosure could be built with relatively low losses and should be the first step towards a fully functioning all solid-state optical refrigerator.

Our Model

- Two Link geometries studies: Tetris and "L"
- Two enclosure types (each coated with Acktar Nano-Black): tight and box of 40 mm on a side
- Two suspension systems: Aerogel and Kevlar



"L" link detailing the materials used for the thermal link in the simulation



Tetris link with Kevlar suspension in a tight enclosure