Modeling the Performance of Optical Refrigerators

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Abstract- **Optical refrigeration using anti-Stokes fluorescence in solids has several advantages over more conventional techniques: including low mass, low volume, potentially low cost, and no vibration. It also has the potential of allowing a miniature cryocoolers on the scale of less than a cubic centimeter. In 2003, we demonstrated the first optical refrigerator that cooled an attached load.**

We have developed a comprehensive system-level performance model of optical refrigerators. Our current version models the refrigeration cycle based on the fluorescent material emission and absorption data at ambient and reduced temperature for the Ytterbium-ZBLAN glass (Yb:ZBLAN) cooling material. It also includes the heat transfer into the refrigerator cooling assembly due to radiation and conduction.

In this paper, we report on modeling results which reveal the interplay between size, power input, and cooling load. This interplay results in practical size limitations using Yb:ZBLAN.

I. INTRODUCTION

The basic principle of cooling by anti-Stokes fluorescence was suggested as early as 1929 [1], but it was not until 1995 that the actual cooling of a solid was first demonstrated by Epstein et. al. at Los Alamos National Laboratory (LANL) using Ytterbium doped Zirconium Fluoride (Yb:ZBLAN) glass [2,3]. In 1996, Clark and Rumbles reported cooling in a dye solution of rhodamine 101 and ethanol [4]. A collaborative effort by LANL and Ball Aerospace resulted in an isolated cylinder of Yb:ZBLAN cooling 48°C below the ambient temperature [5]. Recently, LANL has reported cooling an isolated glass sample to 208 K. [6]. In 2003, we demonstrated the first optical refrigerator. It has cooled an attached load 15.6° C below the surroundings [7].

The fundamental refrigeration cycle of fluorescent cooling is simple. In the case of the Yb: ZBLAN material, the presence of the internal electric fields of the host ZBLAN material cause the ground and first excited states of the Yb^{3+} ion to be split into multilevel manifolds as shown in Fig. 1. A photon from a laser tuned appropriately will be absorbed only by an ion that has been thermally excited to the highest level of the ground-state manifold, and will promote that ion to the lowest level of the excited-state manifold. When that ion decays radiatively, it can fall to any of the four ground-state levels. On average the outgoing fluorescent photon will therefore carry slightly more energy than the pump photon absorbed. By selectively "picking off" the "hottest" ions, this process depletes the population of the highest ground-state level. Thermal equilibrium is reestablished when another ion is promoted to that level by absorbing a phonon from the host material. The absorption of this phonon constitutes the refrigeration.

In summary, a Yb^{3+} dopant ion absorbs a pump photon and the photon is re-emitted slightly bluer (higher energy). This energy difference comes from thermal vibrations (phonons) of host material.

The simplest implementation of a cryocooler based on this principle is a simple Yb:ZBLAN cylinder (cooling element) with high-reflectivity dielectric mirrors deposited on the ends as shown in Fig. 2. The pump beam is introduced through a small feed hole in one mirror, and then bounces back and forth until it is absorbed. A key feature of this arrangement is that the pump light is confined to a nearly parallel beam, while the fluorescence is emitted randomly into 4π steradians. This makes it possible to allow the fluorescence to escape while trapping the pump light inside. The fluorescent photons that are nearly parallel to the pump beam are also trapped. They are reabsorbed and then simply try again to escape with a small and calculable degradation to the overall efficiency.

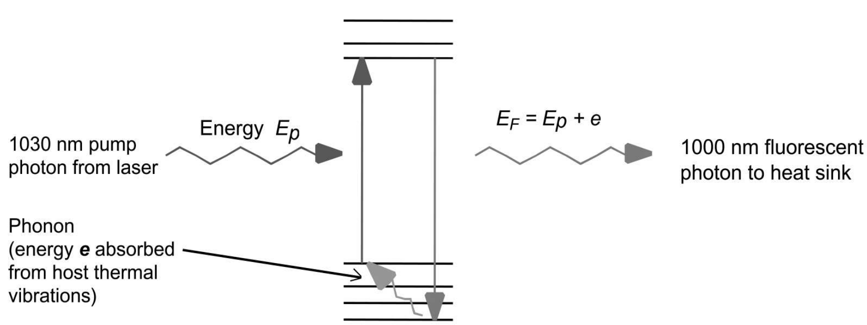

Figure 1. The photon-phonon refrigeration cycle results from the energy levels of the Yb^{3+} ion in the ZBLAN glass host material.

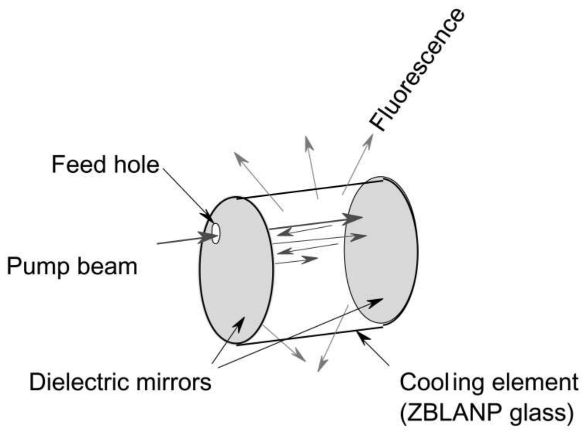

Figure 2. Dielectric mirrors provide long pump path

The potential advantages of optical cooling have been identified in previous work [8]. The overall system mass for mechanical coolers, thermoelectric coolers and optical cryocoolers for an optimized spacecraft application were calculated. An optical cryocooling will likely have the lowest system mass when the load is less than 1.0 W and the temperature is between 80 and 200 K. Optical refrigeration has the potential to extend benefits of solid-state cooling a new, lower temperature region. Optical cryocooling can potentially be miniaturized to a much smaller size than conventional methods

II. CONCEPTUAL REFRIGERATOR DESIGN

Fig. 3 shows our design concept for an optical cryocooler detector dewar. The cooling element is bonded directly to the focal plane structure in order to absorb the heat. The fluorescence is absorbed by a heat sink with high absorbtivity at this wavelength. The cooling element and focal plane are supported by a folded tube of low thermal conductivity material, in a manner similar to dewars that have been used for focal planes cooled by mechanical cryocoolers. Note that the optical cooling element and heat sink are small compared to the structure that is needed to support a focal plane at cryogenic temperatures. A sketch of the laboratory optical refrigerator is shown in **Fig. 3**. The refrigerator is contained in a small vacuum chamber (not shown), which contains a window for the pump beam The vacuum chamber is pumped to a pressure less than 10^{-4} torr using a turbo molecular pumping station. The chamber is maintained at a constant temperature about 10 degrees C above the ambient to eliminate the effect of swings in the laboratory temperature. This allows for more precise measurements of heat conductance and cooling.

A copper heat sink completely surrounds the cooling assembly and is mounted to the vacuum chamber wall. A significant issue with the heat sink is the surface facing the cooling assembly. This surface needs to selectively absorb the near 1 micron fluorescence while having low emittance to the ambient radiation. The cooling assembly, which includes the cooling element, thermal link and the load mass, is mechanically supported within the heat sink using a fiberglass epoxy support.

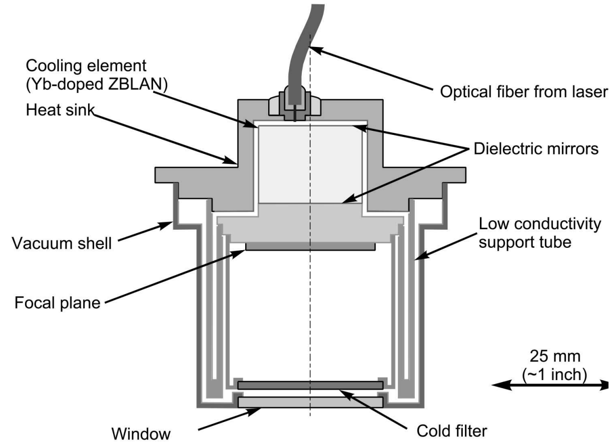

Figure 3. Ball optical cryocooler design concept for an infrared detector/cryocooler dewar. This specific design is capable of producing 400 mW heat lift at 80 K with a 21 W laser when the heat sink is 300 K.

The cooling element is made from Yb:doped Zirconium Fluoride glass (ZBLAN). It is cylindrical and coated on both ends with high performance dielectric mirrors. The cooling element is 12 mm in diameter and 13 mm long and weighs 8.5 grams. It is doped with 2% by mass Ytterbium Fluoride.

A critical issue in the design of an optical refrigerator is that the load to be cooled will invariably be light absorbing and must be shielded from the light from the cooling element fluorescence while being in thermal contact with it. This occurs even when the load appears to be shielded by one of the dielectric mirrors since has been found that the dielectric mirrors leak a significant amount of fluorescence [9]. The cooling element is attached to the load with a proprietary thermal link that provides high thermal conductance but prevents the leaked fluorescence from being absorbed by the load.

The cooling element was pumped using a commercial Yb:YAG disk laser, which could be tuned from 1015 to 1050. Tests were done at wavelengths of 1020 to 1040 nm. The could produce output powers of up to 25 watts but only near the1030 nm optimum power wavelength. The laser powers reported here are our estimate of the laser power at cooling element, based on the power measured at the laser and measurement of the feed optics attenuation.

III. MODEL

We have developed a comprehensive numerical model for optical refrigerators. It is a valuable design tool that provides a way of rapidly exploring and optimizing the design parameters, and to evaluate the suitability of the refrigerator for specific cooling applications. The model consists of three parts: tracing the life history of the incoming pump photons, tracing the life history of the outgoing fluorescent photons, and evaluating the internal and external heat transfer.

The first part of the model calculates the probabilities of five possible fates for each pump photon:

1) Absorption by Yb, which includes the reduction by saturation at high power densities.,

2) Absorption by anything else, including unknown contaminants that can only be described empirically,
3) Leakage out through mirrors,
4) Leakage out through feed hole, and
5) Leakage out through imperfect mirror edges.

The absorption and emission of the photons is a function of temperature, Yb doping, and optical intensity. It is calculated based on a physical model of the temperature dependant Boltzmann population distributions that includes energy level and width, transition strength,s and electron populations in each Yb level. The adjustable parameters of this physical model were obtained from fitting Yb:ZLAN absorption and emission data obtained as several temperatures.

The second part of the model calculates the four possible fates of the emitted photons:

1) Escape through the ends (mirrors),
2) Escape through the sides,
3) Re-absorption by Yb (recycling), and
4) Absorption by anything else, which is assumed to cause heating.

The number fluorescent photons that escape or are reflected back into the cooling element is function of the index of the Yb:ZBLAN and the element geometry.

The average energy of the photons escaping the cooling element is calculated, including the effect of "reddening" due to the fluorescent photons that are reabsorbed and then emitted. The final output of the model is the cooling efficiency for the fluorescent cooling process, calculated by subtracting the pump light energy from the escaping fluorescent energy, and dividing by the pump light energy.

The third part of the model calculates the conductive and radiative parasitic head loads from the refrigerator structure, plus temperature drop within the cooling element, using standard heat transfer analysis techniques. Since it is a glass, Yb:ZBLAN is assumed to have a high absorption of the 10 micron thermal radiation, but it surrounded by a close-fitting low emittance heat sink. The parallel plate grey surface approximation is used for radiation view factors.

The most significant limitation of the model at this time is its restriction to Yb:ZBLAN as the cooling material. We currently have detailed temperature-dependent emission and absorption data only for this material. In addition, the model assumes isotropic absorption and emission, which is valid for ZBLAN and other glassy hosts, but may not be valid for crystal hosts that have different absorption and emission in each crystal axis.

IV. MODELING RESULTS

The model was used to analyze the operation of a small optical cryocooler such as that shown in Fig 3. The cooling element is ZBLAN glass doped with 2% Yb, with a length of 15 mm and a cross sectional area of 50 mm^2. The ends of the cooling element are coated with dielectric mirrors with 99.999% reflectance (which has been achieved on Yb:ZBLAN). The cooling efficiency was compared at high pump power (4W) and low pump power (10 mW) across a range of temperatures and pump wavelengths.

Fig. 4 below shows that the cooling efficiency drops with decreasing temperature as expected because of the reduced populations in the upper energy levels caused by the temperature dependence of the Boltzmann distribution. For

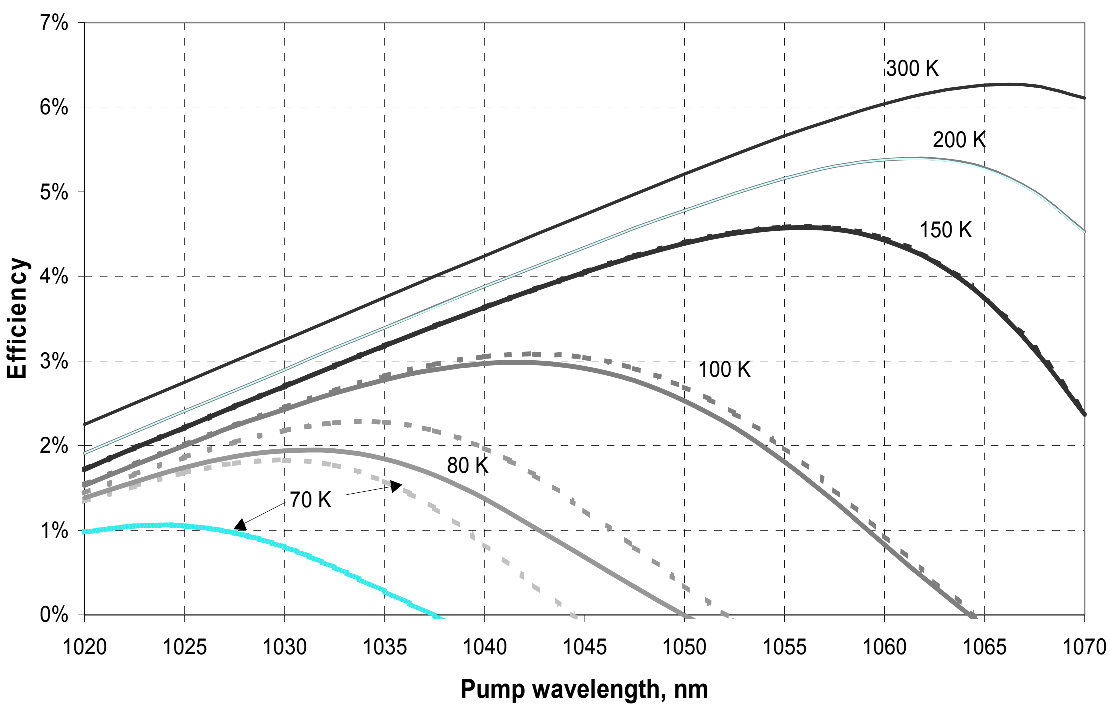

Figure 4. Cooling element performance as a function of temperature and wavelength. The solid lines are with 4 watt input and the dashed lines are with 10 mW input.

each temperature there is an optimum wavelength that results in maximum cooling efficiency, due to competing physical phenomena. Increasing the pump wavelength tends to increase the efficiency by increasing the energy difference between the pump photon and the average fluorescent photon (approximately 990 nm). At longer wavelengths and lower temperatures the, absorption length that the pump light must travel increases, reduces the efficiency due to due to mirror leakage and other losses. At the lower temperatures the effects of saturation of the absorption at high pump power becomes noticeable.

Fig. 5 shows how the available heat lift can be calculated for this particular design. The parasitic heat leak to the cold stage is independent of the pump power. The total heat lift produced varies with temperature and input power as shown. The difference between the heat lift and the parasitic heat load is the cooling power available for a payload. The figure shows that for Yb:ZBLAN, the practical temperature limit is around 70K.

V. APPLICATION TO MICRO CRYOCOOLING

C. T. C. Nyugen [9] has suggested developing cryogenic systems for sensors and other small cryogenic devices that significantly reduce the scale of the cold volume and mass, using precisely targeted cooling, MEMS fabrication, and thermal isolation techniques. By reducing the heat leak significantly, the cryogenic payload can be integrated with a miniature cryogenic refrigerator (micro cryocooler).

Optical refrigeration appears to be well suited for this approach. The vacuum gap between the cooling element and the heat sink allows the parasitic heat loads due to refrigerator to be limited to only radiation. At power levels of less than 300 mW, diode lasers are typically less than 1 mm^3 volume (excluding heat sink). The cooling element volume is inherently small and scales with the required heat lift. The cooling element can be thermally closely coupled with the load, minimizing the cold stage mass.

Our model was used to determine the suitability of an optical refrigerator for using this system concept to produce a highly sensitive portable terahertz detector. A bolometer was packaged with a terahertz antenna and an optical cryocooler into a micro cryostat. Fig. 6 shows the complete system, consisting of the optical refrigerator and bolometer in the micro cryostat, with the antenna visible on the outside. The heat leak into the 90 K cold stage of the cryostat is estimated to be 5 mW.

The cooling performance was modeled to determine the configuration that would most efficiently refrigerate this load. YbF doping of 2 % in the ZBLAN and 99.999% mirror reflectance was assumed. Preliminary modeling showed that the performance was very sensitive to the feed hole size, so a minimum practical size of 50 microns diameter was assumed. Fig. 4 shows that the most efficient wavelength for 90K is 1035 nm, so that was chosen. Cooling element lengths of 2.5 to 40 mm were compatible with the cryostat design, and were therefore modeled and various cross sectional areas. Fig. 7 shows that the efficiency and heat lift of the cooling element improves with length as the number of passes needed to absorb the pump light are reduced. Increasing the cross sectional area initially increases the heat lift, as it reduces the saturation level. But where the saturation level is already low, increasing the cross section reduces the heat lift due to re-absorption of fluorescence. The reabsorption causes a reddening of the escaped fluorescence, moving it closer to the

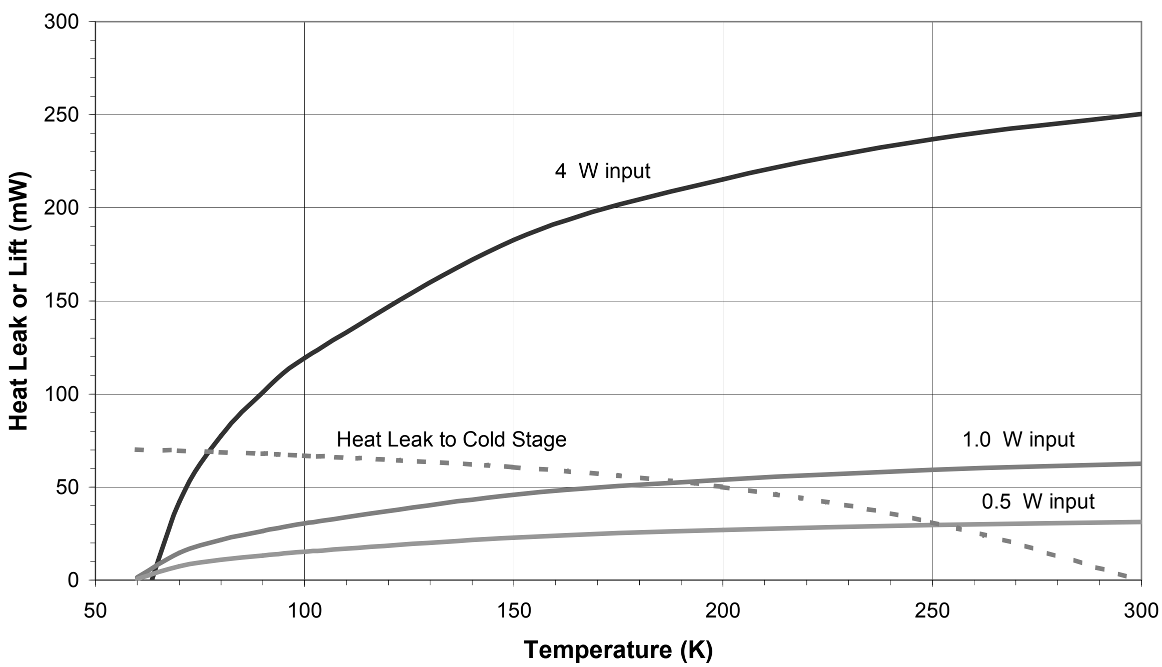

Fig 5. Cooling element performance as a function of temperature and the solid lines are the heat lift and the dashed line is the heat leak to the cold stage

Figure 6 Artists rendering of a micro cryostat containing at terahertz detector and optical refrigerator compared to the size of a quarter. The cryostat has a total volume of 3.0 cubic cm

pump wavelength.

The cooling efficiency drops off rapidly when the cooling element length is less than 5 mm. This appears to be the lower limit of the practical size of a Yb:ZBLAN fluorescent element.

It is clear from Fig. 7, that increasing the length of the cooling element increases the cooling efficiency and heat lift. However increasing the length and cross sectional area also increases the external surface area of the cooling element and the amount it contributes to the total cold stage heat leak. To account for this, we calculated the total heat load (5 mW fixed plus the cooling element radiative heat load) and divided it into the heat lift shown in Fig. 7.

The result is shown in Fig. 8. The optimum fluorescent length appears to be around 10 mm with a optimum cross section of between 8 and 16 mm, or dimensions perpendicular to the length of between 2.8 and 4 mm. This shows the utility of a comprehensive model in optimizing the optical refrigerator design.

VI. CONCLUSIONS

We have developed a comprehensive model of the photon and thermal process of optical refrigerators. Such a model is very useful in guiding the design of the optical refrigerators and optimizing such things as pump wavelength and cooling element geometry.

Further work should be done on the model to extend it to cooling materials other than Yb: ZBLAN, and to address crystalline materials with non-isotropic absorption and emission. Yb:ZBLAN cooling elements probably cannot be practically made with lengths less than 5 mm.

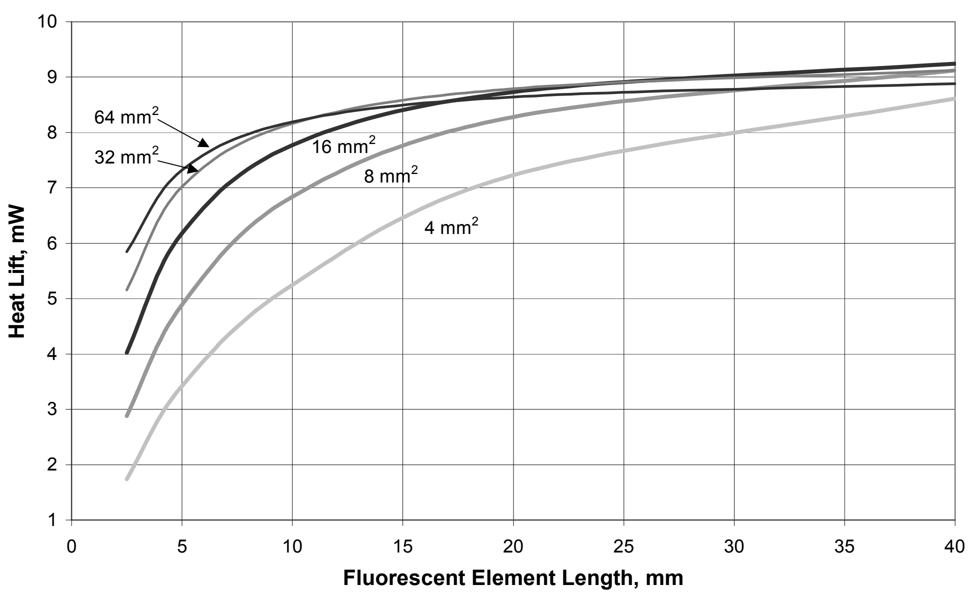

Figure 7: Heat lift for various cooling element configurations pumped with 300 mW at 1035 nm.

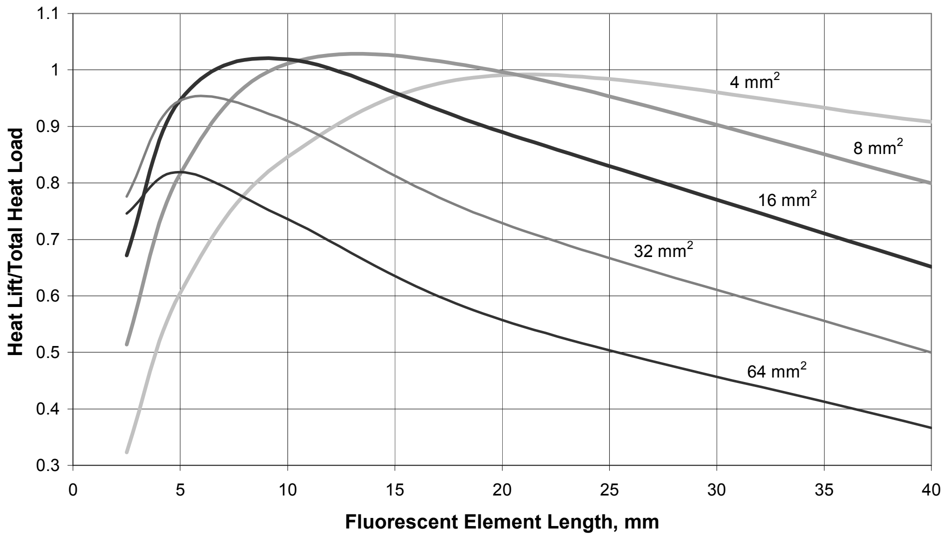

Figure 8: The heat lift divided by the total heat load for various cooling element configurations with a payload heat leak of 5 mW at 90 K with input power of 300 mW.

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