Optical Cryocooling and the Effects of Dielectric Mirror Leakage

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Abstract- **Optical cooling using anti-stokes fluorescence in solids and liquids appears to have several advantages over more conventional techniques and has been the topic of recent analysis and experimental work by numerous organizations. Significant cooling of as much as 65 K below ambient temperature has been reported for isolated samples of cooling material.**

In this paper, we address the problem of thermally connecting the optical cooling element to the cooling load, without having the load heated by absorbed fluorescence. To date, it has been assumed that the load could be shielded from the fluorescence by the use of high performance dielectric mirror stacks in series with the thermal connection. Laboratory observations and extensive analysis of these mirror stacks, using commercially available software, show that significant leakage occurs at large angles of incidence. Because the fluorescence is emitted from the cooling material isotropically, the leakage and resulting absorption at the load can be large enough to negate the cooling effect. We have investigated several variations in mirror design and have concluded that the leakage appears to be inherent to all dielectric mirror stacks and cannot be significantly mitigated through mirror design. We have formulated a solution to this problem and are incorporating the solution into our laboratory optical cryocooler.

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 etal. at Los Alamos National Laboratory (LANL) using Yb 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]. Gosnell has reported cooling of 65 °C in a Yb:ZBLAN fiber [6].

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.

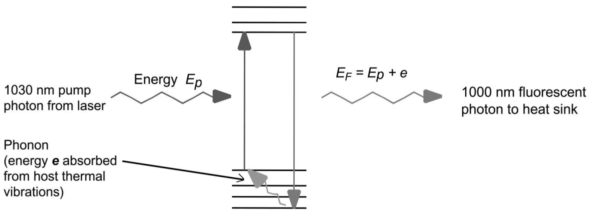

Fig. 1. The photon-phonon refrigeration cycle results from the energy levels of the Yb^{3+} ion in the ZBLAN glass host material.

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.

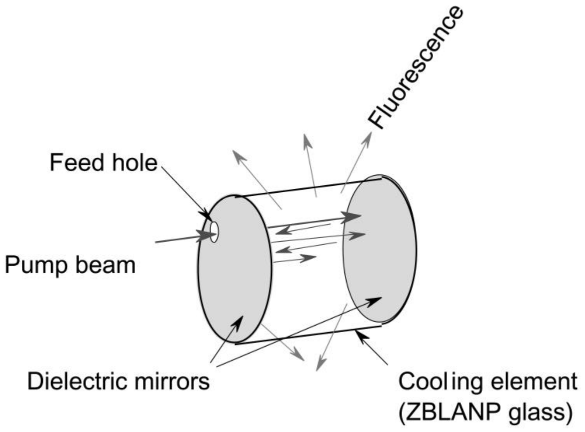

Fig. 2. Dielectric mirrors provide long pump path

In previous work [7], we performed a detailed design study of a complete cryocooler to verify feasibility and to determine the advantages and disadvantages of this technology. We chose to design an optical cooler for cooling a generic focal plane.

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.

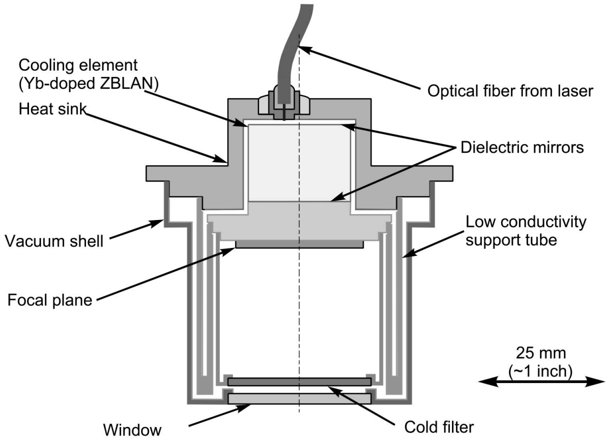

Fig. 3. Ball optical cryocooler design concept for an infrared detector/cryocooler dewar. This specific design is capable of producing 400 mW heat lift at 80 K with a 21 W laser when the heat sink is 300 K.

An optical fiber is aligned and focused to transmit the light from the laser into the cooling element. For the 400 mW cooler shown, a 20 W diode laser package would be required. This would be a package made up of a number of individual diode laser modules, plus optical fiber coupling, with dimensions of approximately 14 cm by 40 cm by 5 cm and a mass of 1.4 kg. It could be located remotely from the dewar to optimize heat transfer from the laser modules, and reduce EMI or magnetic fields, at the focal plane or for other system reasons.

II. COMPARISON TO OTHER REFRIGERATION TECHNOLOGIES

Currently, two different technologies are commonly used to actively cool focal planes, depending on the temperature required. Thermoelectric coolers (TEC) are capable of cooling focal planes to 180 K starting from an ambient temperature of 300 K. They are small, lightweight, and, being solid state, have no vibration. TECs have the main disadvantage of having efficiency that drops off rapidly with decreasing temperature becoming zero around 180 K.

Mechanical coolers, such as Stirling cycle and pulse tube coolers, can produce temperatures below 20 K and are more efficient than TECs. However, mechanical coolers are much larger than TECs and can produce vibrations that must be canceled or isolated.

Based on our design study and experience with TECs and mechanical coolers, we were able to make the following comparisons of optical cooling to the other cooling technologies.

A. Vibration

Because a solid-state diode is used as the pump laser, there are no moving parts and therefore no vibration. This is an obvious advantage for imaging focal planes, an advantage that cannot occur with mechanical coolers. TECs have this advantage as well.

B. Electromagnetic and Magnetic Noise

The pump laser can be located remotely from the cryocooler dewar, allowing very low levels of electromagnetic interference at the focal plane. This can be important if the focal plane contains EMI or magnetic field sensitive devices such as SQUIDs. Optical coolers have this advantage over all other active coolers. Work has been done on split-Stirling cycle coolers with low magnetic noise [8], but such systems have reduced reliability because there is no electric displacer motor to overcome the effects of working gas contamination.

C. Reliability and Lifetime

An optical cryocooler has no moving parts, which enhances reliability and life. The laser appears to be the lifetime-limiting component. Currently, commercial diode modules have a lifetime of several years in continuous operation. A laser package would consist of many laser diode modules feeding a single output optical fiber by using optical Y junctions. This arrangement would have inherent redundancy because the modules almost always fail shorted and have a distribution of lifetimes that is gaussian. Additional redundant modules could be added if necessary.

Some mechanical coolers and TECs have proven lifetimes in excess of five years, however, redundant coolers can be added only with the use of a heat switch because of the high “off-state” conductance of these coolers.

D. Ruggedness

The cooling element is separated from the heat sink by a gap, and thus is inherently protected from physical stress. The glass, although brittle, has a compact form factor that will allow it to withstand high accelerations. TECs and the cold tip of mechanical coolers have to be isolated from loads by S-links or other compliant devices.

E. Cryocooler Mass

The overall estimated optical cryocooler mass, including the laser, will be smaller than a mechanical cooler for typical focal plane cooling loads. An optical cryocooler, however, will be more massive than a TEC. The lack of vibration allows the cooling element to be closely integrated with the focal plane because S-links or other vibration and load isolation devices are not required.

F. Efficiency and System Mass

We have calculated the power efficiency of an optical cooler based on our photon modeling and information from laser vendors. Solid-state lasers currently have an efficiency between 25% and 60% when made up of diode modules. We assumed 50% laser efficiency for the data shown. The lower efficiency of optical cryocoolers and TECs reduces their advantage in power and mass sensitive applications such as spacecraft. Mass is required not only for the power generation, but also for rejecting the waste heat with a radiator. We used overall system mass data for mechanical coolers using data from Glaister et al. [8] For the optical cooler and TEC we used a system penalty of 0.28 kg/W, which is obtained adjusting data from Glaister and Curran [9] to account for the lower structure and heat transport requirements. Based on cooling temperature and load, regions of minimum system mass were determined and plotted in Fig. 4. As shown, for spacecraft applications, 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 cryocooling, in effect, extends benefits of solid-state cooling to this new, lower temperature region.

G. Cost

Optical cryocoolers will be producible at low cost in volume production; there are no high-precision mechanisms involved, and all the components used are ones with proven track records in cost-sensitive applications. Mechanical coolers have inherently high costs associated with high-tolerance moving parts. High-performance, multistage TECs are frequently assembled by hand, but some manufacturers have achieved low cost in volume production of single-stage TECs by using automated assembly. Even the hand-assembled TECs have a large cost advantage over mechanical coolers. Optical coolers are likely to have a similar cost advantage over mechanical coolers.

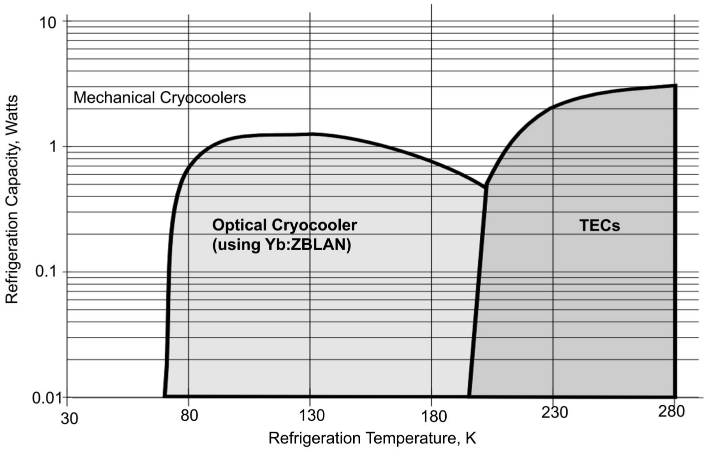

Fig. 4. Approximate regions of lowest system mass for an optimized spacecraft application

III. DIELECTRIC MIRROR LEAKAGE

In the work done to date in optical cooling, it has been assumed that the load could be shielded from the fluorescence by the use of dielectric mirror stacks in series with the thermal connection as is shown in Fig. 3. In the laboratory, we observed fluorescence coming through the dielectric mirror at large escape angles. To understand this, we analyzed the performance of mirror stacks as a function of incident angle, using commercially available thin film software [10].

Dielectric mirrors are most commonly used (e.g. laser cavities) with the incident light on the vacuum or air side and with near normal angles of incidence. Fig. 5 shows that in this case the performance of the mirror is quite high until 50 degrees angle of incidence where it begins to fall off for the P polarization. The S polarization is not affected by the angle.

The situation is different when the light is incident on the mirror from the high-index substrate side. Fig. 6 shows the result for a dielectric mirror in the arrangement required for optical cooling, where the incident medium is the ZBLAN glass cooling element. The mirror is in contact with a YAG substrate, which acts as the thermal conductor to the load. This results in much greater mirror leakage for both polarizations.

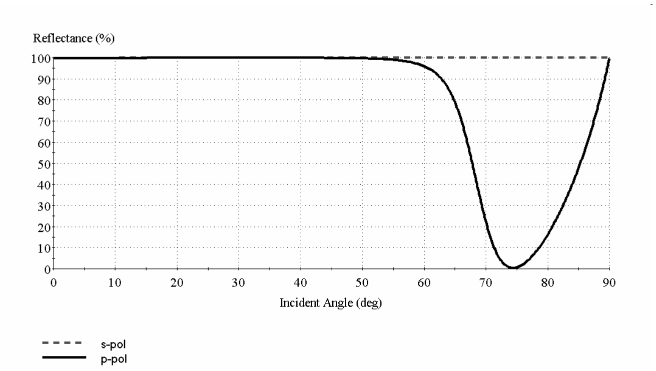

Fig. 5. Reflectance as a function of incident angle at 975 nm with incident medium air. 27 Layer Quarter-Wave dielectric stack of silica and tantalum pentoxide on Yb:ZBLAN substrate at design wavelength of 1064 nm.

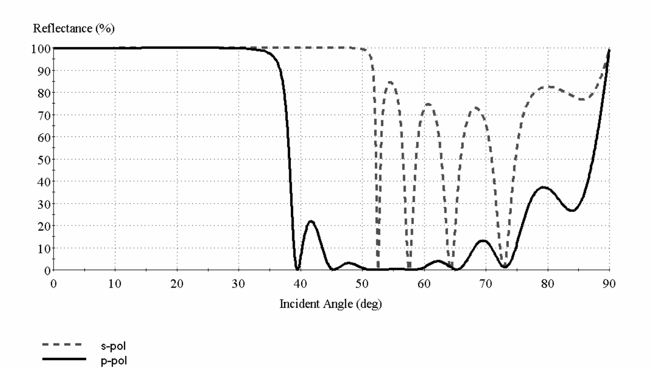

Fig. 6. Reflectance as a function of incident angle at 975 nm with an incident medium of ZBLAN glass. Quarter-Wave stack of 27 layers of silica and tantalum pentoxide on Nd:YAG substrate at design wavelength of 1064 nm.

The fluorescence is emitted within the cooling material isotropically and will be incident on the mirror at all angles. The mirror leakage show in Fig. 6 and the resulting absorption of energy at the load can be large enough to negate the cooling effect. The implications of these results were significant and unexpected enough that we confirmed them using a commercially available ray trace software package [11]. As can be clearly seen in Fig. 7 the results are identical to those in Fig. 6.

In an effort to mitigate the mirror leakage, a layer of silver was added to the mirror stack. The results are shown in Fig. 8. Including an optically thick layer of silver on the exit face of the quarter wave dielectric stack does not reflect all of the light leaked at oblique angles of incidence; instead all of the light transmitted by the dielectric coating is absorbed by the silver layer, making the layer essentially “black.” This occurs because the dielectric multilayer acts as an anti-reflection coating on the silver, allowing more of the light to penetrate the silver layer where it is efficiently absorbed.

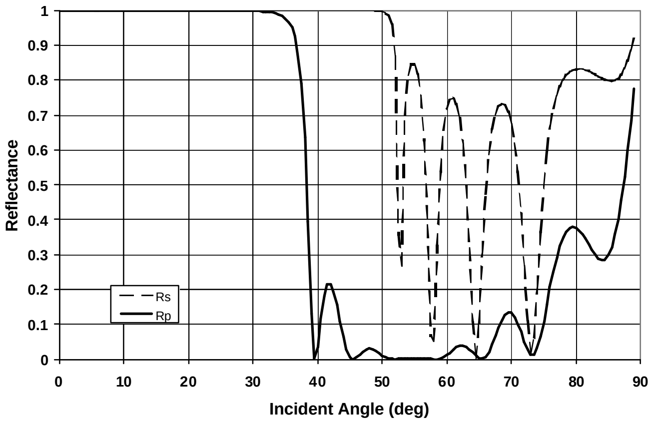

Fig. 7. Reflectance as a function of angle using for the conditions of Fig. 6 using ray trace software.

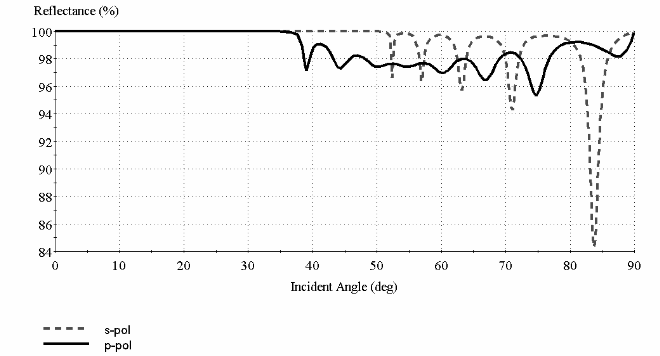

Fig. 8. Reflectance as a function of incident angle at 975 nm with incident medium ZBLAN glass. 27 layer Quarter-Wave stack of silica and tantalum pentoxide on silver layer and Nd:YAG substrate at design wavelength of 1064 nm.

In another effort to mitigate the mirror leakage, stack materials with higher refractive index were considered. For the visible-NIR spectral region, the greatest available dielectric material refractive index contrast comes from zinc sulfide and magnesium fluoride. With dielectric mirrors a large refractive index contrast produces a large region of high reflectance as a function of incident angle. Note that even the index contrast of the ZnS and MgF2 is insufficient to reflect all of the S- and P-polarized light between 40 and 90 degrees at 975 nm as shown in Fig. 9. This behavior is typical of dielectric mirrors in the visible-NIR spectral region because of the limited refractive indices of dielectric materials available in these spectral regions.

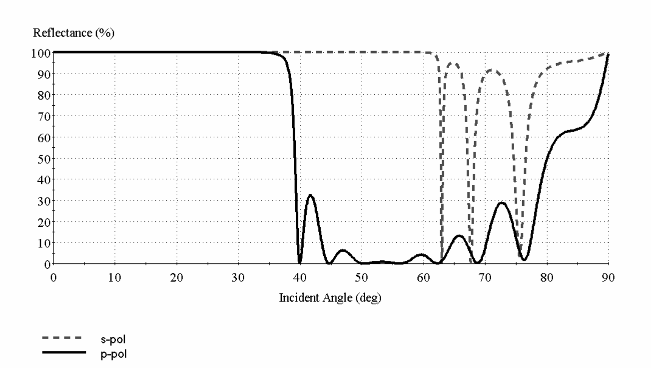

Fig. 9. Reflectance as a function of incident angle at 975 nm with incident medium Yb:ZBLAN. Quarter-Wave stack of 27 layers of ZnS and MgF2 on Nd:YAG substrate at design wavelength of 1064 nm.

IV. EFFECT ON OPTICAL COOLER PERFORMANCE

The effect of mirror leakage on optical cooling performance is significant. Using the ray trace software, we have calculated that 27% of the light emitted by the cooling element leaks through a typical mirror stack and might be incident on the cooling load. Since the available heat lift ranges from 1 to 6% of the fluorescence, depending on temperature, the energy from the leakage has the potential to significantly reduce or even completely negate the cooling effect.

V. CONCLUSIONS

Based on our design and analysis, we conclude that optical cryocooling is a feasible method for cooling focal planes and has a distinct niche in extended solid-state cooling to those temperatures that cannot be achieved efficiently (or at all) by TECs.

We have analyzed the dielectric mirror stacks, which are required for such a cooler using commercially available software, and have found that significant leakage occurs at large angles of incidence. We have investigated several variations in mirror design and have concluded that the leakage appears to be inherent to all dielectric mirror stacks and cannot be significantly mitigated through mirror design. This leakage has the potential to negate the cooling effect.

We have formulated a solution to this problem and are currently testing it in our laboratory at Ball Aerospace.

ACKNOWLEDGMENT

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