Final Technical Report

DOE Award: DE-SC0006450; Office of Science SBIR

Recipient:

ThermoDynamic Films LLC
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Santa Fe, NM 87505

Project Title: “No-Vibration Agile Cryogenic Optical Refrigerator”

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Subcontractor: The University of New Mexico

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Executive Summary

Optical cryocoolers are devices that use laser light to cool small crystal or glass cooling elements [MSB07, RIE09]. The cooling element absorbs the laser light and reradiates it at higher energy photon, an example of anti-Stokes luminescence. The difference between the energy of the outgoing and incoming light (photons) comes from the thermal energy of the cooling element, which in turn becomes colder. Currently, the most successful cooling element is Yb:YLF, which we have cooled from room temperature to 123 K with about 1.5% efficiency during the Phase I period of this SBIR. Optical refrigeration (or laser cooling of solids) is currently the only all-solid-state cryocooling technology (i.e. without any moving parts) that has been demonstrated.

The demonstration of 123 K refrigeration by optical cooling performed by the co-PIs of this proposal during the Phase I project is a first step toward revolutionizing cryogenic systems for sensor applications to enable the transition of this scientific breakthrough into NNSA sensor applications.

Rugged, compact, quiet cryogenic refrigerators are essential for a wide range of emerging space-borne and ground-based non-proliferation and defense applications. Optical refrigerators have the potential to meet these national security and commercial needs. In particular, cryogenic optical refrigerators are well suited to cooling space-borne radiation detectors and infrared imagers in small satellites where low weight and lack of vibrations are especially important. For example, optical cryocoolers could cool infrared detectors for DOE's remote sensing program and the Department of Defense's Space-Based Infrared System. These satellites, which provide enhanced strategic and theater ballistic missile warning capabilities, require cryogenic cooling and are very sensitive to vibration. Compact optical refrigerators could also be used with medical technology, eliminating the need for bulky cooler or the storage of volatile liquid nitrogen.

Background:

Optical refrigeration or laser cooling of solids is the subject of intense current interest because it can be exploited to achieve an all-solid-state, high performance refrigerator [BCE98, RIE09]. This rapidly emerging technology offers the advantages of compactness, high reliability, no vibrations, no moving parts, and no need for cryogenic working fluids. Performance at the lowest temperatures well surpasses thermoelectric coolers, the primary competing solid-state refrigeration technology. Space-borne infrared sensors that are flown on ion propulsion vehicles and unmanned aerial vehicles with extended flight times are certain to benefit from continued development.

The essential concept of optical refrigeration is illustrated in Fig. 1 for a two-level atomic system with broad ground- and excited-state manifolds. Photons from a low-entropy light source (i.e. a laser) with energy $h\nu$ excite atoms from the top of the ground state to the bottom of the excited state. The excited atoms reach quasi-equilibrium with the lattice by absorbing phonons (yellow arrows). Spontaneous emission (fluorescence) follows with a mean photon energy that is higher than that of the absorbed photon ($h\nu_F > h\nu$). This process is also called anti-Stokes fluorescence.

Figure 1. Concept of optical refrigeration. Pumping with photons of energy $h\nu$ less than the mean luminescence energy $h\nu_f$ can lead to the radiative removal of thermal energy.

The cooling efficiency η_c , defined as ratio of the cooling power to the absorbed power, is given by [MSB07] ,

$$\eta_c = \eta_{ext} \eta_{abs} \frac{h\nu_f}{h\nu} - 1 \quad (1)$$

where the product of external quantum efficiency (η_{ext}) and pump absorption efficiency (η_{abs}) describes the probability of conversion of an absorbed photon at $h\nu$ to a fluorescence photon with mean energy $h\nu_f$ exiting the material. The latter accounts for loss of pump light to parasitic background absorption, and the former describes reduction of cooling efficiency due to: i) luminescence trapping in the sample and ii) optical excitations that recombine non-radiatively. When these efficiency coefficients are significantly less than unity, undesired heating will occur. Understanding, quantifying, and addressing these two efficiencies (η_{ext} and η_{abs}) has been the key to attaining efficient optical cryo-cooling.

In 1995, net laser cooling in solids was first achieved at Los Alamos National Laboratory (LANL) by one of this proposal's PIs [RIE95]. Two technical challenges were addressed and overcome in these experiments. A material system was needed in which i) the vast majority of optical excitations recombine radiatively and ii) there is minimal parasitic heating due to unwanted impurities. It is also important that spontaneously emitted photons escape the material without being trapped and re-absorbed, which would effectively inhibit spontaneous emission. This is a critical issue for directly cooling high-refractive-index semiconductors such as GaAs, where total internal reflection can cause strong radiation trapping [MSB07]. A conceptual diagram of a laser-cooled sensor is presented in Fig. 2. A compact diode laser serves as the pump; absorption is enhanced by arranging the sample between two mirrors to recirculate the pump. The mirrors form a non-resonant optical cavity. The sample is also situated inside a shield to reduce the radiative heat load. The shield serves the auxiliary purpose of dumping luminescence into a heat sink. If the

cooling luminescence can be converted to electrical energy via strategically placed photo-cells, such a device can approach the Carnot efficiency limit [MSB09]. In all applications, the cooling element has to be connected to the device being cooled (i.e. the load) by a thermal link. This link siphons heat from the load while preventing the waste fluorescence from heating it.

Figure 2. (left) Illustration of a laser-cooled infrared detector. The thermal link provides a conductive contact between the cooler and detector but also shields it from anti-Stokes fluorescence (blue wavy lines). (right) Schematic of a compact diode-pumped optical refrigeration system.

In recent years the PIs on this proposal and their students and colleagues have greatly advanced optical cryocooling. Much of this work was funded by an AFOSR MURI award program at University of New Mexico (UNM) during 2004-2009. A summary of some of the major findings of this effort follows:

In 2009, the UNM group achieved record cooling with an Yb-doped YLF crystal grown at the University of Pisa, Italy [DVS10]; the Yb:YLF crystal cooled by 150 degrees with respect to the thermally shielded enclosure (clamshell) and reached an absolute temperature of 155 K. The cooling power (i.e. heat lift) was over 100 mW at the lowest temperatures attained. To put this result in perspective, all-solid state commercial thermoelectric coolers based on the Peltier effect require multiple stages to approach an absolute temperature of 170K with heat lift of < 50 mW. During the Phase I of this SBIR, even lower temperatures and higher powers were achieved: 123K and 180 mW; see Fig. 11, below. These results are discussed in more detail below under “Degree to which Phase I has Demonstrated Technical Feasibility”

The pump radiation is derived from a commercial continuous-wave Yb:YAG disk laser (ELS Versadisk). For the first demonstration of cooling to 150 K, pump laser was tuned to 1023 nm where the output power is ~10 W. To achieve lower absolute temperatures, (Fig 3) during the Phase I, we applied more power at the optimal wavelength of 1020 nm, as discussed below.

The limits of Yb:YLF cooling can be understood through analysis of a separate experiment to ascertain the minimum achievable temperature (MAT). The cooling efficiency described by Eq. (1) depends on wavelength and temperature as follows:

$$\eta_c(\lambda, T) = 1 - \frac{\eta_{ext}(T)}{1 + \alpha_b / \alpha_r(\lambda, T)} \times \frac{\lambda}{\lambda_f(T)} \quad (2)$$

Temperature-dependent fluorescence spectra provide the mean fluorescence wavelength $\lambda_f(T)$; a similar measurement gives the temperature-dependent absorption $\alpha_r(\lambda, T)$. Over the range of pump wavelengths (λ) the background absorption can be taken as constant at $\alpha_B = 4 \times 10^{-4} \text{ cm}^{-1}$, determined in a separate experiment. Results of this analysis for 5% doped Yb:YLF are presented in Fig. 3. Pumping the $E4 \rightarrow E5$ transition of Yb^{3+} (left, insert) at 1020 nm can lead to an absolute temperature of $\sim 110 \text{ K}$, provided there is sufficient laser power available (right panel).

Figure 3. (left) Analysis of the minimum achievable temperature in Yb:YLF crystal as a function of pump wavelength from Eq. (2) [DVS11]. In the contour plot on the left, blue indicates pump wavelengths and temperatures where cooling occurs. Red corresponds to heating. The data represent local cooling measurement in agreement with our model. The lowest temperature is achieved by pumping at 1020 nm, corresponding to the E4 to E5 transition (see insert) in Yb ion. The right side shows the predicted and measured cooling temperatures for various pump wavelengths and powers. The record data (obtained recently as part of phase-I efforts) shows cooling to 123K and 118K from room temperature. [SDM12B]

To effectively cool Yb:YLF crystals we acquired of an ytterbium fiber laser system that operates at maximum of 60 W at $\lambda \sim 1020 \text{ nm}$. With it, we were able to set new performance milestones in laser cooling of solids and brought optical refrigeration into cryogenic temperature regime as defined by the National Institute of Standards ($< 123 \text{ K}$). The recent milestone achieving cryogenic operation in Yb:YLF can be better appreciated by examining the record minimum temperature versus year since the realization of optical refrigeration in 1995 (Fig. 4). With further purification to reduce α_b to $1 \times 10^{-4} \text{ cm}^{-1}$ and/or increasing the Yb^{3+} doping concentration, cooling down to 70 K with Yb:YLF is within reach.

Figure 4. Record minimum temperature has decreased since the first demonstration of laser cooling of fluoride glass at LANL in 1995. The “Peltier barrier” at 170 K was broken with Yb:YLF in 2009. The “NIST crogenic barrier” at 123 was surpassed during the Phase I work. The next big goal is to reach liquid nitrogen temperature at 77K.

In optical cryocooling, the cooling power scales with optical excitation up to a saturation level. The cooling power dependence can be understood as follows. For a single excited ion, the amount of cooling power is $(h\nu_f - h\nu)/\tau_r$ where τ_r is the excited state lifetime dominated by the radiative component. Since the number density of ions occupying the E_4 Stark level in the ground state is the maximum number of ions that can be excited, the maximum cooling power density is:

$$p_c = \left(\frac{N_0 Z_4 e^{-(E_4 - E_1)/kT}}{\sum_{j=1}^4 Z_j e^{-E_j/kT}} \right) \left(\frac{h\nu_f - h\nu}{\tau_r} \right) \quad (3)$$

where N_0 is the doping number density and E_j 's and Z_j 's are the energy and degeneracy factors of the ground state Stark manifold of Yb^{3+} for a given host.

Assuming the practical condition of $h\nu_f - h\nu \sim kT$, $\tau_r \sim 3$ ms, and using the published spectroscopic data for Yb:YLF [AS06], we obtain a maximum cooling power density given by:

$$p_c (W/cm^3) \approx [\text{mol}\%][0.6 \times T(K)] e^{-650/T(K)} \quad (4)$$

which is plotted in Fig. 5. For example, for mol%=5 (5% doping), Eq. 4 yields cooling power densities of $\sim 1 \text{ W cm}^{-3}$ and $\sim 20 \text{ W cm}^{-3}$ at 100 K and 200 K respectively. These heat lift capacities far exceed the demands of most space vehicle refrigerators.

Figure 5. Calculated cooling power density for 5% doped ytterbium-doped YLF.

Anticipated Public Benefits

In many areas of national defense, scientific and laboratory analytic instruments, medicine and high performance electronics, it is necessary to cool instruments and devices to cryogenic temperatures (below $-150^{\circ}\text{Celsius}$). *Cryocoolers* are essential components in the infrared (IR) systems that are used for defense applications such as surveillance and ballistic missile guidance. Cryocoolers are an important part of the U.S. government's priority of heightened homeland and international military security. This focus includes infrared surveillance and direct defense imaging applications (satellite and ground), as well as precision target identification for military action.

Cryocoolers are considered critical parts in a variety of defense applications, in particular infrared surveillance techniques in Intelligence, Surveillance, and Reconnaissance and for Ballistic Missile Defense applications. More specifically, optical cryocoolers can improve the performance and reliability of the infrared surveillance missions of the Space-Based Infrared System (SBIRS) and Space Tracking and Surveillance System (STSS). These views were validated by Erin Pettyjohn, Director of Spacecraft Component Thermal Research Group at AFRL, Kirtland AFB, based on strict specifications of US Air Force for space-based and airborne IR surveillance.

Current cryocooler technologies use cryogenic liquids (e.g., liquid nitrogen or liquid helium) and/or methods based on mechanical or acoustical systems (e.g., compressors or pulse tubes) [JHA06]. These conventional mechanical coolers continue to suffer from significant disadvantages such as bulky size, high power consumption, noise and vibrations, which will hamper their use as the requirements for IR sensing become increasingly more stringent.

With no moving parts, *TDF's* solid-state optical refrigerators would not be subject to wear. Additionally, they do not utilize any fluids, which can leak and generally need replenishing. These features alone constitute substantial advantages over the current technology. Additional advantages include the compactness of these refrigerators, total lack of vibrations, agility, greater temperature stability, the absence of electromagnetic interference (EMI) and more rapid cool down. These advantages are particularly compelling for aerospace applications, such as those for space-borne infrared sensors. DoD has identified specific goals for future cryocoolers, which optical refrigeration is capable of satisfying.

The elimination of microphonic noise: Since optical refrigerators are the only solid-state technology that can cool from room temperature to cryogenic temperatures, it is uniquely capable of satisfying this goal.

Low-mass gimbaled agility: Optical cryocoolers have the advantage that their most massive components, i.e. the pump laser and its power supply can be remotely located from the cooling element. The laser light is guided using a flexible fiber that is thermally isolated from the active load. This capability allows for construction of an extremely low mass cooling head, which in turn, lends itself to highly agile gimbaled applications. Currently, this is achieved in mechanical cryocoolers by separating the compressor and cold finger connected with cryogenic transfer tubes; this increases the complexity, mass, thermal load, and unwanted thermal parasitics.

Micro-scalability for single pixel cooling: Optical refrigeration has the great advantage of micro-scalability, limited in principle to the size of the optical wavelength. This allows selective and controllable cooling of small-scale structures, such as a single or group of pixels on an IR sensor and permits compensating for non-uniform thermal load on an FPA system. In addition, by local delivery of cooling to small critical components, optical refrigerators can reduce the overall power consumption, --a vital advantage for space-born missions and for handheld applications.

Controlling thermal jitter: The temperature stability of cryocoolers based on optical refrigeration revolutionizes performance over mechanical systems, by taking advantage of the speed and precision of an optical system. Focal plane arrays inevitably are subjected to a variety of changing thermal environments, yet must have their temperature stabilized to less than 0.1 K variations. This can be challenging for mechanical systems, however the optical cryocooler can achieve stability to less than 0.005 K [SEL09].

No electromagnetic Interference: Since optical cryocoolers are driven by laser light, no electrical power enters the cooling element. This is advantageous when cooling sensitive electronic components because it eliminates the risk electronic coupling between the cooler and the device being cooled.

Ability to cool rapidly: Mechanical cryocoolers typically require hours to cool a sensor to operational temperatures. In contrast, an optical refrigerator can cool to cryogenic temperatures in a matter of minutes. Consequently, imaging systems could be idled at much higher temperatures and brought into operational condition in a matter of minutes.

Technical Achievements of the Phase I SBIR Project

The technical objectives of our Phase I work were to design prototype vibration-free optical cryocoolers that can approach temperatures of 77 K with practical (low resistance) thermal links. We conducted key experiments (Fig. 4, 11) together with theoretical modeling (Fig. 3) to validate predictions for the performance of optical cryocooler crystals in the range of 70-100K with watts of cooling power. As described below, our Phase I activities successfully achieved a number of key milestones in optical refrigeration. These included cooling to temperatures below NIST-defined cryogenics (123K), demonstrating the first intracavity laser cooling using a semiconductor laser (VECSEL), and showing the feasibility of distributed Bragg reflector (DBR)-on-Sapphire technology.

Designing Prototypes

We concentrated on two principal design concepts: a Diode-pumped Intracavity Solid-state Cryo-Cooler (DISCC) (Prototype 1, Fig. 6) and an Externally Pumped Optical Cryo-Cooler (EPOCC) (Prototype 2, Fig. 10). The experiments we carried out used the Yb-doped YLF crystal (the most successful optical cooling material to date). The techniques, diagnostics and pumping schemes we developed are general and applicable to other rare-earth doped materials such as crystals doped with holmium, thulium and erbium. Both the DISCC and EPOCC cryocooler configurations are inherently compact and low mass with the complete absence of mechanical jitter. Optical feedback is easily incorporated to help improve thermal stability and performance as well. The EPOCC prototype is capable of being scaled to low powers and miniaturized.

Prototype 1: Diode-pumped Intracavity Solid-state Cryo-Cooler (DISCC)

Figure 6. Schematic of a Diode-pumped Intracavity Solid-state Cryo-Cooler (DISCC).

As illustrated in Fig. 6, the DISCC prototype cryocooler is based on an intracavity-enhanced absorption scheme utilizing an optically-pumped semiconductor laser (OPSL). These lasers are also called vertical external cavity surface-emitting lasers (VECSEL); we will use the latter terminology hereafter. The diode pump laser light (nominally at 810-900 nm) is delivered by a fiber and focused onto an InGaAs multiple quantum well (MQW) gain chip, designed to operate at $\lambda=1020$ nm. This chip is grown epitaxially on top of a distributed Brag reflector (DBR). To control its temperature, the MQW/DBR chip is bonded to a diamond substrate, which is in turn attached to a copper heat sink. The cooling element, a 5-10 mm 5% doped Yb:YLF crystal, is Brewster-cut (to minimize reflection losses) and is carefully held inside a tight “clamshell” chamber using six fused-silica fiber posts. The inside walls of the clamshell are coated with low-emissivity coating, which efficiently absorbs the fluorescence while minimizing the thermal radiation. The laser cavity is completed with a highly reflecting (HR) dielectric mirror. In this design, the thermal link is attached to the load on the side of the cooling crystal, as shown in Fig. 6. For illustration purposes it is shown as a truncated pyramid of sapphire [JP09].

Proof-of-Concept Demonstration: As VECSEL technology is relatively young [OG010], a high-performance gain chip at a particular wavelength is not commercially available. It requires multiple design and epitaxial growth sequences to converge to a working device with optimum characteristics. For this task, we collaborated with Sandia National Laboratories (Albuquerque, NM) to develop the desired VECSEL chip. After a few iterations of growth and characterization, we obtained an operating chip with high quality performance at the designed wavelength of 1020 nm. The design of the VECSEL gain chip, illustrated in Fig. 7, consists of a DBR and a MQW gain region. The DBR consists of 25 pairs of quarter-wave optical thickness AlAs/GaAs layers. Twelve InGaAs quantum wells (QWs) in a resonant periodic gain structure are placed at adjacent antinodes of the standing wave inside the semiconductor subcavity. The barrier between the QWs, typically GaAs, has been replaced with $\text{GaAs}_{0.97}\text{P}_{0.03}$ for strain compensation. The structure is completed by a lattice-matched InGaP window layer, transparent to both the VECSEL emission and pump light, which provides carrier confinement.

Figure 7. Index of refraction n and calculated electrical field strength E along the growth direction z of the 1020 nm VECSEL gain chip [ARA12].

For thermal management, which is necessary for high power operation, the DBR is metalized with titanium, gold, and indium and soldered to a 300 μ m thick thermal-grade polycrystalline CVD-grown diamond heat spreader, which is metalized in the same way. After the growth, the substrate is removed using a selective wet etch, terminated at the InGaP layer. During operation, the diamond is cooled using a custom water jet impingement technique, where a high velocity liquid jet from a 1 mm diameter nozzle cools the diamond plate directly behind the gain chip.

Prior to performing intracavity cooling, we tested the VECSEL performance using a simple external cavity as shown in Fig. 8 (left) where the mode size at the VECSEL sample is matched to the roughly 300 μ m diameter pump spot created by focusing the light from a fiber-coupled 808 nm pump diode.

Figure 8. (left) Schematic diagram of simple VECSEL test setup. (right) Identifying the 1020 nm chip with record (20%) slope efficiency [ARA12].

As shown in Fig. 8 (right), some of the VECSEL chips operated at 1020 nm with a world record slope efficiency of 20%. The lasing wavelength and its linewidth can be precisely controlled by inserting spectral selective elements, such as birefringent filters.

Demonstration of the intra-cavity DISCC proof-of-principle prototype: As shown in the diagram of Fig. 9, a 2mm Yb:YLF (5%) crystal in a vacuum chamber is placed in the light path of the laser cavity. This experiment was performed with an earlier VECSEL chip that was tuned only to wavelengths above 1025 nm. The preliminary results nonetheless were extremely promising: a 20 K temperature drop was measured in vacuum, starting from room temperature. As with any intra-cavity-enhanced absorption process, a critical (optimum) coupling condition can be met by adjusting the integrated resonant absorption for a target temperature (e.g. 120 K). This is achieved by properly selecting the length and doping concentration of the Yb:YLF sample. With our new VECSEL chips, efficiently operating at the optimum wavelength of 1020 nm, together with reduction of ambient thermal load (using clamshell housing), a compact DISCC device capable of cooling to 120K appears quite feasible.

Figure 9. (a) The intra-cavity cooling arrangement using InGaAs VECSEL gain chips and (b) its laboratory experimental implementation. (c) Measured temperature drop after turning the pump laser on at wavelength of 1025 nm [ARA12].

Prototype 2: Externally Pumped Optical Cryo-Cooler (EPOCC)

The Externally Pumped Optical Cryo-Cooler (EPOCC) concept (Fig. 10) differs from that of DISCC (Fig. 6) in that pump laser light at $\lambda \sim 1020$ nm is delivered to the cooling head by a fiber from a laser that is remote from the cryocooler. Additionally, the enhancement of the laser light in the cooling cavity is achieved through a multipass nonresonant scheme. Again, the design parameters are for a Yb:YLF crystal, but they can be generalized to other rare-earth ions and hosts. The external laser can be either a fiber laser (Yb-fiber) or a diode laser operating at 1020 nm. The pump laser is coupled through a hole in the front dielectric mirror and is carefully aligned to obtain 6-10 roundtrips. The coatings on the cooling chamber and the thermal link are the same as for the DISCC device.

Figure 10. Schematic of an Externally Pumped Optical Cryo-Cooler (EPOCC) using a Yb:YLF crystal. The laser light at 1020 nm is carried by a fiber and coupled through a hole in the entry mirror. The thermal link and cold finger configuration is similar to that in the DISCC device (Fig. 6).

Demonstration of an externally pumped EPOCC proof-of-principle prototype:

For this purpose, a high power (60 W), linearly polarized Yb-doped fiber laser operating at 1020.8 nm (line width <0.5 nm) was custom made for us by IPG Photonics. This is a robust turn-key system with a wall-plug efficiency exceeding 30%. The laser is coupled into a non-resonant (multi-pass) cavity after passing through an isolator and mode matching optics, as depicted in Fig. 11 (left). A tight-fit clamshell housing, coated with low-emissivity foil, was used to minimize the ambient radiative load. The cooler is housed inside a vacuum chamber at 10^{-6} torr to eliminate heat conduction through air. The cooling sample, a Brewster-cut 5% doped Yb:YLF crystal is held inside the clamshell using 4 silica fiber supports. The preliminary experiments led to a new record and milestone in optical refrigeration: The Yb:YLF cooled from room temperature to 123 K, which is defined by NIST as the onset of cryogenic temperatures [SDM12B].

The cooling power in the experiment of Fig. 11 (right) is estimated to be about 180 mW (corresponding to an absorbed power of 12 W and cooling efficiency of $\sim 1.5\%$). **This achievement validates the technical feasibility of the optical cryocooler as a vibration-free alternative to mechanical cryocoolers, down to temperatures approaching 100 K.**

The multipass cavity of Fig. 11 currently supports a maximum of six roundtrips. As the sample cools down, the resonant absorption is reduced, which consequently lowers the total absorbed power. Since the fractional temperature drop obeys $\Delta T/T_0 \sim P_{cool}/P_{load}$, the minimum achievable temperature can be approached by either increasing the cooling power ($P_{cool} = \eta_c P_{abs}$) or reducing the thermal load. Since the dominant thermal load is radiative, we reduced it by cooling the clamshell to 210K with liquid nitrogen. With this change, laser cooling of Yb:YLF crystal down to 118K was possible, consistent with our modeling and setting a new cooling record.

Figure 11. The proof-of-concept prototype EPOCC device on the left and the record-breaking cooling data on the right.

Thermal Link Designs: The cooling element of an optical refrigerator cools nearly uniformly as heat is removed by the luminescence. To cool a load, such as an infrared detector, the cooling element of an optical refrigerator has to be linked to the load, so it can draw heat from it (Fig. 12). This coupling sets up a temperature gradient between the element and the load. In a good thermal link, this temperature gradient has to be minimized. At the same time, virtually none of the luminescence can impinge on any parts of the load, otherwise radiative heating could easily overwhelm the optical refrigeration effect.

Figure 12. Kink-style thermal link. Heat from the load readily diffuses around the kink. The luminescence largely escapes from the sides of the link when it encounters the sharp angle.

We have performed preliminary calculations of generic thermal links [JP09]. One promising approach is to use transparent, tapered thermal links made of materials that are good thermal conductors, such as sapphire; see Fig. 13. A dielectric mirror between the cooling element and the thermal link and/or between the thermal link and the cold finger prevents the laser light and much of the luminescence from reaching the load. Light at large angles, however, will pass through the mirror and move toward the load. If the link is tapered, each successive internal reflection drives the luminescence to steeper incidence angles. Preliminary calculations show that most of the luminescence leaks out of the sides of the thermal link, so that very little impinges on the load.

As part of Phase I effort, we analyzed simple fluorescence-shedding geometries involving no-kink and single-kink thermal links, made of sapphire and one dielectric mirror. Using ZEMAX ray-tracing software, we evaluated the fluorescence rejection. In our ray-tracing analysis, we assumed that a high quality reflector is bonded to the end of the thermal link. The fluorescence rejection factors for three simple geometries (from many geometries that were considered) are illustrated in Fig. 13.

Fluorescence Rejection Factors

Figure 13. Fluorescence rejection factors for three illustrative thermal link designs.

We note that the right-angle structure performs superbly as it transmits only 0.001% of the fluorescence. This is quite remarkable and far exceeds our expectations, considering the simplicity of the structure. These results further eliminate the need for considering textured kinks (described in the Phase-I tasks), since texturing can make the thermal link susceptible to surface contamination and parasitic absorption of the fluorescence [SDM12A].

Epitaxial DBR on Sapphire - Concept and Implementation:

Although the thermal conductivity of thermal link material (sapphire) is very high, conventional amorphous dielectric mirrors (based on MgF_2) introduce further thermal resistance. Moreover, low index contrast in such dielectric stacks, limits the solid angle of the high reflectivity cone, allowing significant leakage of the isotropic fluorescence light. To alleviate this problem, we investigated the use of epitaxially-grown semiconductor-based DBR structures, that are lifted-of and bonded to the thermal link using Van der Waals bonding.

We implemented this concept successfully during the Phase I program. A GaAs/AlGaAs DBR comprising a stack of 12 quarter-wave pairs was epitaxially grown on GaAs substrate at UNM's Center for High Technology Materials (CHTM). A thin (50 nm) AlAs release layer was sandwiched between DBR and substrate, thus allowing lifting of the DBR section in an HF etching process as shown in Fig. 14. A proprietary method has been developed to perform the lift-of and bonding process of large area DBRs, without compromising their optical and mechanical properties. The initial proof-of-principle experiments were conducted using glass (as opposed to sapphire) as the thermal link. The measured reflectivity before and after the process was determined to be identical; exceeding 99.5% at normal incidence. Thermal conductivity analysis based on the available data has shown that more than a 40-fold enhancement is expected over standard dielectric mirrors. [SDM12A]

Figure 14. The processes for creating DBR-on-sapphire reflectors. The steps include epitaxial growth, mounting a wax bead on the DBR, wet-etch lift off, and Van der Waals bonding on the new substrate.

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