Journal of the Optical Society of Korea, Vol. 10, No. 2, June 2006, pp. 57-62

A Cooled Deformable Bimorph Mirror for a High Power Laser

Jun Ho Lee*
Dept. of Optical Engineering, Kongju National University, Kongju-si, Chungnam, KOREA

Young Cheol Lee and Eung Cheol Kang
Agency for Defense Development, P.O. Box 356, Yuseong, Daejon, KOREA

(Received April 18, 2006 : revised April 18, 2006)

Adaptive optics (AO) has been applied in various fields including astronomy, ophthalmology and high power laser systems. An adaptive optics system for a high power laser is not significantly different from other AO systems in the point of configuration except that high energy absorbed by the deformable mirror distorts the deformable mirror surface and so degrades system performance. Currently we are researching a bimorph deformable mirror for beam cleaning of a high power class laser. The bimorph mirror was considered to have 99% reflective coating and 1% absorption. So this paper first presents the temperature profiles and corresponding thermal distortions of the bimorph mirror faceplate when the mirror is under a high power lasing for 10 seconds. The analysis was accomplished by the use of finite difference and finite element computer programs to generate the element arrays, calculate the temperature profiles, and determine the structural deformations. Then this paper proposes an 'embedded wafer' type water-cooling system with derived cooling parameters.

OCIS codes : 010.1080, 140.0140, 140.3320, 230.4040

I. INTRODUCTION

Adaptive optics systems remove the wavefront distortion introduced by a turbulent medium by introducing a controllable counter wavefront distortion which both spatially and temporally follows that of the atmosphere [1]. Adaptive optics has been prominently used in astronomy for compensating the wavefront aberrations induced by the earth's atmosphere. Nowadays adaptive optics has been applied in other applications such as high power laser system [2], ophthalmic system [3], laser communications [4], microscopy [5] and under-water imaging system [6]. Conventional adaptive optics systems work in a closed-loop configuration in which the phase control element such as a deformable mirror is iteratively adjusted to null the residual phase measured by a wavefront sensor.

An adaptive optics system for high power laser is not significantly different from other AO systems in the point of configuration except that high energy absorbed by the deformable mirror distorts the deformable mirror surface so degrade system performance.

Since high power laser systems have thermal distortions problems, previous studies have been carried out on the thermal effects due to high power laser, and on cooling mechanisms to overcome the thermal effects. Szetela and Chalfant showed that the temperature rise in a chemical laser mirror can results in severe distortion of the mirror surface in forms of curvature variation [7] and Kelin solved state-state heat balance equations for high-power CW laser windows [8]. Ealey and Wellman reported an efficiently cooled laser mirror in 1993 [9] and a cooled mirror for a double-undulator beamline was also reported [10]. The first three used forced convection as a cooling mechanism while the last used the contact or conduction cooling.

Safronov studied a cooled single channel bimorph mirror [11-12]. He used a cooling system of the 'oblique wafer' embedded in underneath of the reflective surface of the mirror. He proposed that such a cooling system allows using the cooled bimorph mirrors in laser systems, the integral radiation power of which may reach 10 kW. Vorontosov and others also reported an adaptive cooled mirror for the resonator of an industrial laser [13].

Currently we are researching a bimorph deformable mirror for beam cleaning of a high power laser [14,15]. So this paper first presents the temperature profiles and corresponding thermal distortions of the bimorph mirror when the mirror is under a high power lasing. The analysis was accomplished by the use of finite difference and finite element computer programs to generate the element arrays, calculate the temperature profiles, and determine the structural deformations. Then we adopted Safronov's cooling system to our mirror and derived cooling parameters.

II. DESCRIPTION OF THE BIMORPH MIRROR

A bimorph mirror with 32 actuators was selected as the deformable mirror for our research. Fig. 1 shows the schematic drawings of the deformable mirror and Fig. 2 shows a model used in finite element analysis (FEA) software. The front surface of the deformable mirror is single crystalline Si of 3mm thickness and is coated for reflection. It has a clear aperture of 120 mm and was edge-mounted by a support structure at the diameter of 150 mm. It has 30 mm further distance from the edge of the third-ringed actuators to the mounting structure for allowing the deflection at the edge of the clear aperture. A reflection coating was deposited on the front surface of the Si membrane and the reflectance of the coating was considered to 99%.

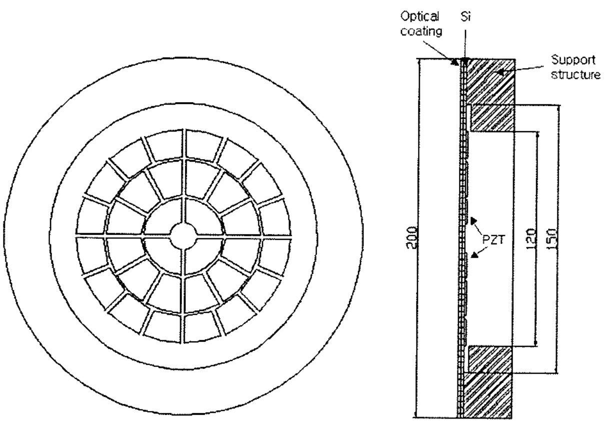


FIG. 1. Schematic drawing of the bimorph deformable mirror.

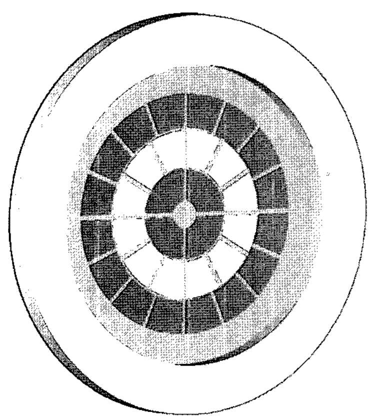


FIG. 2. Finite element analysis model of the bimorph mirror.

III. THERMAL EFFECTS OF THE UNCOOLED BIMOHRPH MIRROR

1. Thermal conditions including laser thermal loading

A study on the bimorph mirror found that an effective area for wavefront correction is an annulus of outer diameter 100 mm and inner diameter 20 mm [14]. In addition, since the bimorph mirror can be used for a holed-square beam as shown in Fig. 3, we consider three different thermal loadings: 1) circular laser beam, 2) an annulus laser beam and 3) square laser beam. The lasing time was considered to be 10 seconds and the power of the lasing was set to 100 KW. The reflectance of the deformable mirror was considered to be 99% so the absorption coefficient was considered to be 1%. Table 1 summarizes the relative properties of the bimorph mirror substrate Si and table 2 summarizes the thermal loading conditions. The initial temperature of the bimorph mirror was set 0℃ just for the easiness of calculation.

2. Thermal analysis results

Based on the previously established thermal model and loading conditions, we performed transient thermal

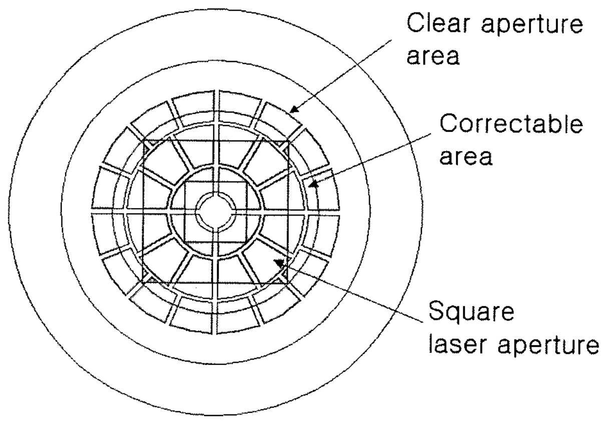
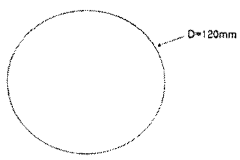
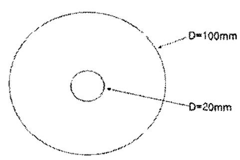
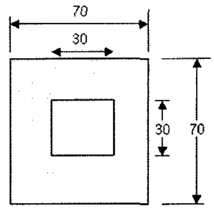


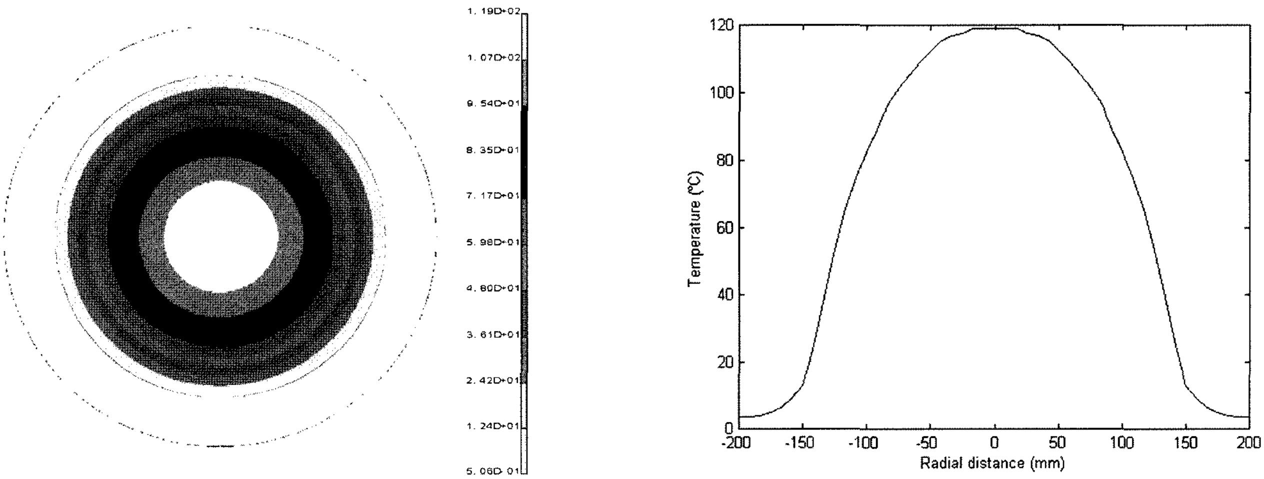
FIG. 3. The correctable area of the bimorph mirror with our square laser beam aperture.

TABLE 1. Parameters of single crystalline Si mirror substrate.

Thickness	3 mm
Young's Modulus (E)	13.1 Gpa
Poisson's Ratio (v)	0.279
Coefficient Thermal Expansion	2.7 e-6 /℃
Density	2.329 g/cm^3
Specific heat	660 J/Kg·K
Conductivity	158 W/m·K

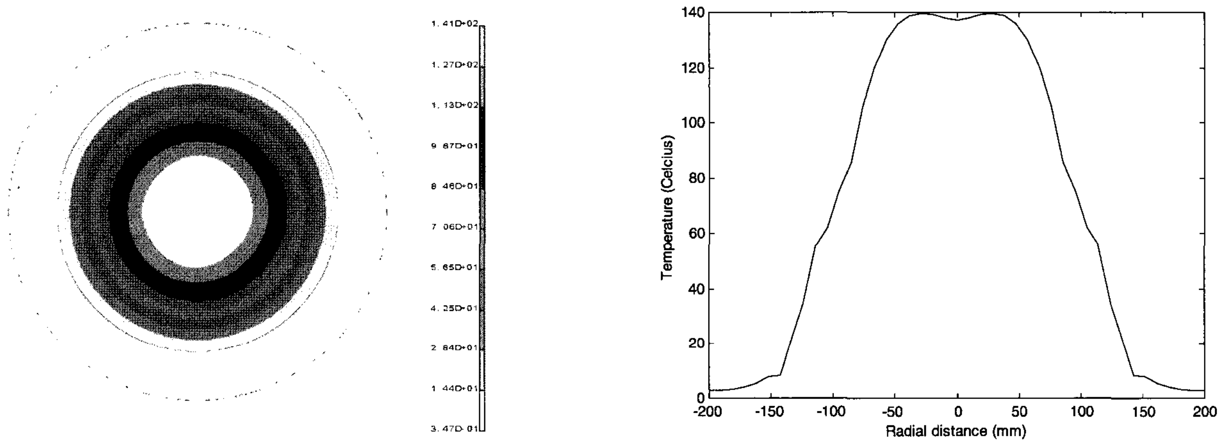
TABLE 2. Three thermal loading conditions when the lasing power is 100 KW.

Case	Circular beam	Annulus beam	Holed square beam
Thermal loading regimes			
Absorbed power (1% absorption)	1 kW	1 kW	1 kW
Absorption area	113.1 cm^2	75.4 cm^2	40 cm^2
Absorbed heat flux	0.9 kW/cm^2	1.3 kW/cm^2	2.5 kW/cm^2



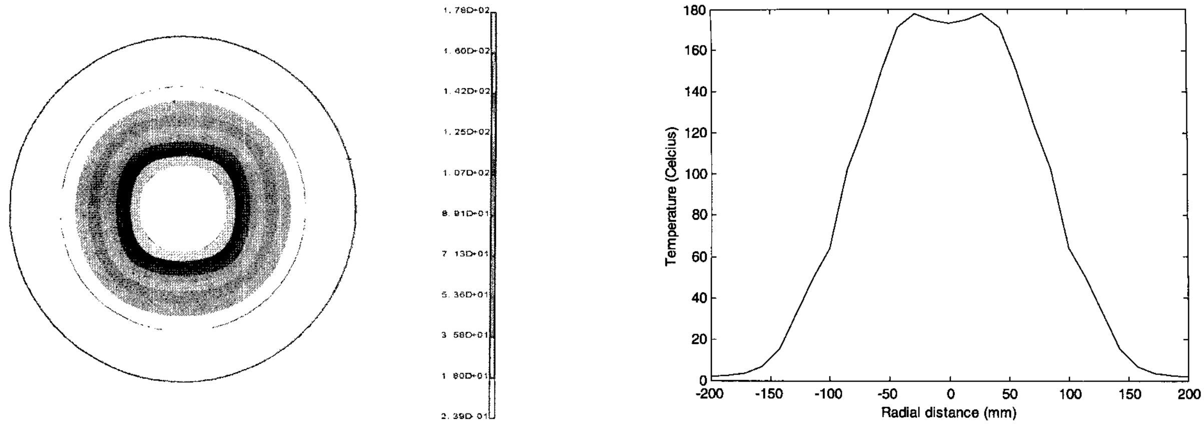
(a) Temperature profile over the faceplate (b) Temperature profile along the radial direction

FIG. 4. Temperature profiles of the faceplate after a circular laser beam of 100 kW (ϕ=120 mm) is lased on the bimorph mirror for 10 seconds.



(a) Temperature profile over the faceplate (b) Temperature profile along the radial direction

FIG. 5. Temperature profiles of the faceplate after an annlus laser beam of 100 kW (ϕ_{out}=100 mm, ϕ_{in}=20 mm) is lased on the bimorph mirror for 10 seconds.



(a) Temperature profile over the faceplate (b) Temperature profile along the radial direction

FIG. 6. Temperature profiles of the faceplate after a holed square laser beam of 100 kW (70 mm × 70 mm) is lased on the bimorph mirror for 10 seconds

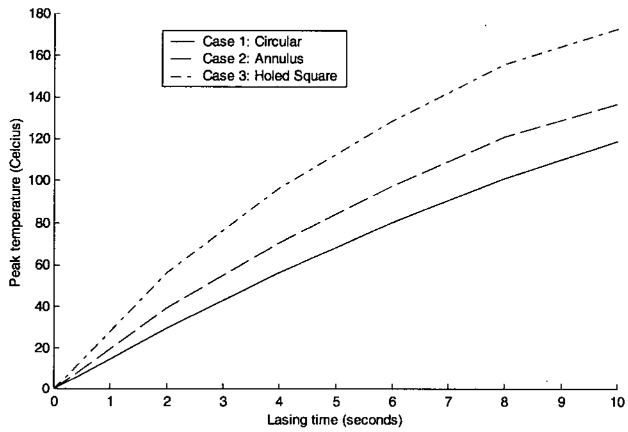


FIG. 7. Change of the peak temperatures of three cases as the lasing time increased

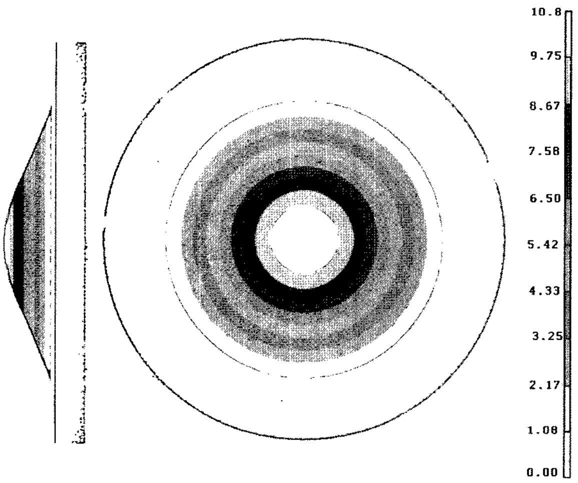


FIG. 8. The deformation of the bimorph mirror due to lasing of 100 kW for 10 seconds (The unit in this figure is microns.)

analysis by commercial finite difference and element analysis software. Figs. 4~6 show the temperature profiles of the mirror faceplate after 10seconds' 100 kW lasing. The peak temperatures of the three cases are 119℃, 137℃ and 173℃. Fig. 7 shows the peak temperature changes of the three cases as the lasing time increased. Fig. 8 shows the deformation of the bimorph mirror due to the thermal lasing.

IV. COOLING OF THE BIMORPH MIRROR

1. Cooling idea

The previous section 3.2 shows that the peak deformation of the bimorph mirror is up to 11 μm under 10 seconds' lasing of 100 kW, which is not acceptable for the bimorph mirror to keep its capability of correcting aberrations. Therefore, the bimorph mirror must be actively cooled. In addition, the heating is not efficiently conducted over the mirror surface due to the low conductivity of the mirror material Si. So the absorbed heat remains around the central part of the mirror, which deforms the curvature of the bimorph mirror due to the low conductivity of the mirror material Si.

Here we use conduction-convection cooling system. The cooling system is basically identical to the water-cooling system used in the previous studies [11-13]. The cooling system is formed underneath the reflective surface of the mirror. A coolant (water) is supplied to the cooling system. Unlike the previous, our system has a middle metal coating layer for conduction. The layer increases the total thermal conductivity of the bimorph mirror, which decreases the temperature and temperature gradient. Fig. 9 shows the schematic diagram of the cooled bimorph mirror. A dielectric layer was laid underneath the metal coating for the easiness of bonding.

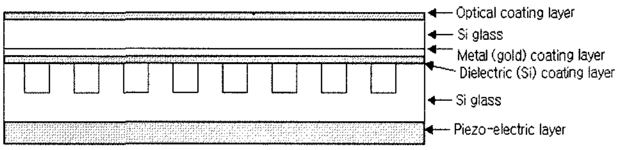


FIG. 9. Cross sectional view of the central part of the bimorph mirror

The thickness of metal coating was set to be 50 μm therefore the metal coating layer does not change rigidity of the mirror neither cause so-called 'bi-metallic' bending due to temperature differences between two layers. The size of the water channel is one third of the membrane thickness i.e. 1 mm and the channels are 1 mm spaced along the vertical direction.

2. Cooling parameters

Here we calculate the cooling parameters to cool down the mirror. The coolant water is considered an incompressible and constant property fluid. Table 3 lists the basic thermo-physical properties of water.

The water-cooling system uses the forced convection. The total heat transfer rate of the convection q may be expressed as

$$q = hA(T_{mirror} - T_{water}) \tag{1}$$

where h is a convection coefficient, T_{mirror} the surface temperature where the convection occurs, T_{water} the temperature of the water flow.

Since the heat transfer rate varies depending on the difference between the surface temperature and the temperature of water flow, the heat transfer rate varies depending on the location of convection. However, total heat transfer rate along a water channel can be given by the following equations [16]. Table 4 summarizes the results of the equations.

$$q_{total} = \int hA(T_{mirror} - T_{water})dl \approx \bar{h}LA(\bar{T}_{mirror} - \bar{T}_{water} \tag{2}$$

$$\bar{h} = Nu_D \frac{k}{D_h} \tag{3}$$

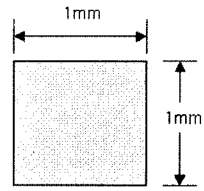
$$D_h = \frac{4A_c}{P} \tag{4}$$

where $\bar{h}$ is the average convection coefficient along the water path, $\bar{T}_{mirror}$ the average temperature of the mirror surface along the water path, $\bar{T}_{water}$ the average temperature of the water along the water path, Nu_D Nusselt number, k the conductivity, D_h the effective diameter or hydraulic diameter, A_c the flow cross sectional area and P the wetted parameter.

TABLE 3. Thermophysical properties of water at 300K [16].

Specific heat (Cp)	4179 J/kg K
Viscosity (μ)	855×10^{-6} N×s/m^2
Thermal conductivity (k)	0.606 W/m×K
Pandtl Number (Pr)	5.83

TABLE 4. Parameters of a single-channel water-cooling

Parameters	Value
Cross section	
Hydraulic diameter (D_h)	1 mm
Nusselt number (Nu_D)	3.61
Average convection coefficient ($\bar{h}$)	2.2 KW/m^2·K

The total absorbed heat flux is 1 kW for our case. Since water-cooling channels are spaced with 1 mm distance, there are 50 channels within the diameter of 100 mm so average cooling capability per channel should be 20 W. However, as shown in Fig. 7, the peak temperature of the bimorph mirror is about 2.5 times higher than the average temperature. Therefore, the maximum cooling capability per channel should be 2.5 times higher than the average cooling capability, which is 50 W.

From heat transfer and energy conservation laws, the following equations can be derived.

$$\dot{m} = \rho A_c V = \frac{50\,W}{C_P(T_{out} - T_{in})} \tag{5}$$

$$\frac{T_{out} - \bar{T}_{mirror}}{T_{in} - \bar{T}_{mirror}} \approx \exp\left(-\frac{\pi D_h L}{\dot{m} C_P}\bar{h}\right) \tag{6}$$

where $\dot{m}$ is the mass flow of water, ρ the density of water, V is the flow velocity, T_{in} the temperature of water at inlet, T_{out} the temperature of water at outlet and L the length of water-cooling channel.

The temperature of water at inlet T_{in} was assumed to be a room temperature (25℃) and the length was considered as 150 mm. $\bar{T}_{mirror}$ was ~ 75℃ which was the mean temperature solved from the square laser beam (case 3).

Solving the previous equations together by numerical analysis, we get the cooling parameters such as the water flow rate as follows:

$$T_{out} \sim 30℃ \text{ or } \Delta T = T_{out} - T_{in} = 5℃ \quad (7)$$

$$\dot{m} = 2.39g/\sec \quad (8)$$

$$V = 2.4m/\sec \quad (9)$$

However, we should be careful that $\dot{m} = 2.39g/\sec$ is for a single channel so the total water flow depends on the number of channels. We should have $\dot{m}_{total} = 359g/\sec$ or $\dot{m}_{total} = 239g/\sec$ for 100 and 150 channels, respectively.

V. CONCLUSION

We performed thermal and structural analysis of a bimorph mirror under 100 kW lasing for 10 seconds. We found that the peak temperature of the bimorph mirror rises up to ~180℃ when a square laser beam is used. The thermal deformation is up to ~11 μm. Therefore, an active cooling must be used for the mirror to keep its capability to compensate cavity-induced aberrations.

We adopt a well-known water-cooling system in order to cool the bimorph mirror. In addition, we propose a conduction layer should be in the bimorph mirror to increase the cooling efficiency and reduce the temperature gradient which distorts the mirror. We also derived some cooling requirements such as water flow rate for cooling the mirror.

Further works shall be on the finite difference and element analysis of the mirror including the conduction layer and the enforced convection flow.

*Corresponding author : jhlsat@kongju.ac.kr

REFERENCES

[1] J. M. Beckers, "Adaptive Optics for Astronomy: Principles, Performance and Applications," *Annual Review of Astronomy and Astrophysics*, vol. 31, pp. 13-22, 1993.

[2] A. V. Kudryashov and V. V. Samarkin, "Control of high power CO_2 laser beam by adaptive optical elements," *Optics Communication*, vol. 118, pp. 317-322, 1995.

[3] J. L. Gargasson, M. Glanc, and P. Léna, "Retinal Imaging with adaptive optics," *C.R. Acad. Sci. Paris.*, t.2, Série IV, pp. 1131-1138, 2001.

[4] S. Arnon and N. S. Kopeika, "Adaptive optical transmitter and receiver for space communication through thin clouds," *Applied Optics*, vol. 36, no. 9, pp. 1987-1993, 1997.

[5] Z. Kam, B. Hanser, M. G. L. Gustafsson, D. A. Agard, and J. W. Sedat, "Computational adaptive optics for live three-dimensional biological imaging," *PNAS*, vol. 98, no. 7, pp. 3790-3795, 2001.

[6] M. L. Holohan and J. C. Dainty, "Low-order adaptive optics: a possible use in underwater imaging?," *Optics & Laser Technology*, vol. 29, no. 1, pp. 51-55, 1997.

[7] E. J. Szetela and A. I. Chalfant, "Thermal distortion of mirrors," *Thermochimica Acta*, vol. 26, pp. 191-197, 1978

[8] C. A. Klein, "High-Power CW Laser Windows: Edge-Cooled or Face-Cooled?," *Proc. SPIE*, vol. 1739, pp. 230-253, 1992.

[9] M. A. Ealey and A. Wellman, "Cooled ISOFLOW laser mirrors," *Proc. SPIE*, vol. 1739, pp. 374-382, 1993.

[10] Y. Li, A. M. Khounsary, J. Maser, and S. Nair, "Cooled mirror for a double-undulator beamline," *Proc. SPIE*, vol. 5193, pp. 204-210, 2004.

[11] A. G. Safronov, "Controllable bimorph optics based on piezoelectric structures," Ph. D. thesis, General Physics Institute of Russian Academy of Sciences, 1995.

[12] A. G. Safronov, B. S. Vinevitch, and V. M. Zharikov, "Controllable curvature mirrors for laser techniques", *Proc. SPIE*, vol. 3686, pp. 16-25, 1999.

[13] M.A.Vorontsov, G.M.Izakson, A.V.Kudryashov, G.A. Kosheleva, S.I.Nazarkin, Yu.F.Suslov, and V.I.Shmalgauzen, "Adaptive cooled mirror for the resonator of an industrial laser," *Sov. J. of Quantum Electron.*, vol. 15, p. 888, 1985.

[14] J.H. Lee, Y.C. Lee, and H. J. Cheon, "A circular bimorph deformable mirror for circular/annulus/square laser beam compensation," *J. Opt. Soc. Korea*, vol. 10, no. 1, pp. 23-27, 2006.

[15] Jun Ho Lee, Tae-Kyung Uhm, and Sung Kie Young, "First-Order Analysis of Thin-Plate Deformable Mirrors," *J. Kor. Phys. Soc.*, vol. 44, no. 6, pp. 1412-1416, 2004.

[16] F. Incropera and D. P. De Witt, *Introduction to Heat Transfer*, John Wiley & Sons, 2^{nd} Ed., 1990.