Quantum Electronics **33** (7) 655 – 658 (2003)

PACS numbers: 42.79.-e; 44.10.+i
DOI: 10.1070/QE2003v033n07ABEH002474

Thermal stability parameters of cooled optical elements

V.V. Apollonov, A.M. Prokhorov, V.A. Shmakov

***Abstract*. The effect of a coolant on the thermal stability of cooled optical elements is studied. A new stability parameter containing the characteristics of a system for cooling optical elements and of the coolant is proposed.**

Keywords: *optical elements, heat exchange, stability parameters.*

One of the basic requirements imposed on materials of optical elements is the preservation of their optical parameters. Usually, the following optical characteristics are estimated: the reflection and scattering coefficients, complex refractive index, coefficient of thermal expansion, density, heat conduction, specific heat, and melting temperature.

No less important also are

(i) mechanical parameters: the elastic modulus, ultimate strength, microplasticity, yield strength, hardness, and forgeability;

(ii) metallographic parameters: the crystal structure, grain size, recrystalisation temperature, stress removal temperature, texture, heat treatment type, presence of the second phase, pores, and impurities; and

(iii) technological parameters: the possibility of mechanical machining, polishing, and coating deposition.

The disadvantage of optical elements made of copper, glass ceramics, fused silica, pyroceram [1 – 3], etc., which are commonly used in high-power lasers and astronomy, is their high coefficient of thermal expansion or low heat conductivity. For this reason, they cannot be efficiently employed in the case of intense light fluxes and a rapid change in the environment temperature. In addition, an increase in their size under the condition that the initial shape of the optical surface is preserved under the action of gravitational forces and thermal stresses leads to a drastic increase in their mass. The traditional designs of such optical elements and the technological features of their manufacturing do not allow any substantial reduction in their weight and the development of the efficient cooling and thermal stabilisation system.

We have shown in this paper that the stability of cooled optical elements depends to a great extent on the parameters including the characteristics of a coolant and a heat exchanger.

The thermal stability of optical elements as a function of their thermal load is determined by a number of parameters [4 – 6].

According to the criterion of achieving the critical temperature T_c on a reflecting surface, the stability parameters for optical-element materials for cw and pulsed lasing have the form

$$\max\{\lambda T_c\}, \qquad \max\{(\lambda c\rho)^{1/2} T_c\},$$

where c is the specific heat capacity; λ is the thermal conductivity; and ρ is the material density. The meaning of the critical temperature depends on specific conditions. This can be the recrystallisation temperature, phase transition temperature, etc. Hereafter, 'max' means the maximum admissible values of a given parameter for a material under study at which the optical element is still operable.

A part of radiation absorbed by an optical surface converts to heat, producing heat flows in the material. An inhomogeneous temperature distribution appearing in the optical element gives rise to heat stresses. If the maximum shear stresses produced by the heat flows exceed the yield strength of the material, the irreversible structural changes take place. The corresponding stability parameters of the material according to the criterion of achieving plastic deformations on the optical surface for cw and pulsed lasing have the form

$$\max\left\{\frac{\lambda\sigma_0}{\beta E}\right\}, \qquad \max\left\{\frac{(\lambda c\rho)^{1/2}\sigma_0}{\beta E}\right\},$$

where σ_0 is the yield strength; β is the coefficient of thermal expansion; and E is the Young modulus.

The quantities σ_0 and E should be considered simultaneously because a high level of heat stresses $\sim\beta E/\lambda$ will not produce structural changes in the material if the yield strength is high enough. For brittle materials, the quantity σ_0 should be treated as the brittle fracture stress or the stress producing the development of microcracks. Plastic materials are characterised by the value of the residual deformation deteriorating the optical quality of the reflecting surface. The critical stress σ_0 is determined experimentally in this case (usually, the stress producing the residual deformation equal to 0.01 is chosen). In the case of repetitively pulsed laser irradiation, the fatigue damage of the material should be taken into account.

V.V. Apollonov, A.M. Prokhorov, V.A. Shmakov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia

Received 16 January 2003
Kvantovaya Elektronika **33** (7) 655 – 658 (2003)
Translated by M.N. Sapozhnikov

The thermoelastic deformation of the reflecting surface of optical elements is one of the basic characteristics and determines to a great extent the quality of laser radiation. According to the criterion of achieving the ultimate deformation of the optical surface, the stability parameters of the material for cw and pulsed lasing can be obtained by solving the model thermoelasticity problems

$$\max\left\{\frac{\beta}{\lambda}\right\}, \qquad \max\left\{\frac{\beta}{c\rho}\right\}.$$

For each of these lasing regimes, there exists the most 'strict' stability parameter, which limits the use of materials in optical elements. In the case of cw lasing, two parameters describing thermoelastic and plastic deformations of the optical surface are important. In the case of pulsed lasers, the parameters describing the critical temperature produced on the optical surface and the conditions of plasma formation play a significant role. As the laser pulse duration is decreased, the energy deposition being invariable, the parameters describing melting and evaporation of the material and the appearance of the near-surface plasma become important. If the pulse duration is $\sim 10^{-9}$ s and shorter, dynamic effects become significant. In this case, the velocity of elastic waves and a finite velocity of heat transfer should be taken into account.

Some requirements imposed on cooled optical elements can be incompatible. These are, for example, stability parameters determined by the ultimate heat flow and the ultimate thermal deformation of the optical surface. The optimisation of the design of optical elements to reduce their thermal deformations gives rise to additional stresses preventing the distortion of the optical surface. This reduces the ultimate heat flows producing plastic deformation of the surface. In addition, the reduction of the size of some elements in a heat exchanger to improve the efficiency of a cooling system deteriorates the strength of laser mirrors.

The choice of stability parameters for optical elements in cooled cw lasers is determined by the properties of heat exchange depending on the heat exchanger design and the coolant parameters, which can substantially change the type of deformation.

The temperature field of a cooled optical element is essentially inhomogeneous. The temperature drop occurs predominantly in a thin near-surface layer containing a reflecting plate and a heat exchanger. The heat exchange occurs due to heat transfer, while the thermal conductivity plays a less significant role than in uncooled optical elements.

Fig. 1 shows the dependence of the deformations of the reflecting surface on the thermal conductivity calculated for the cooled optical element of characteristic size 500 mm with $\beta = 1.7 \times 10^{-7}$ K^{-1} (copper). One can see that the dependence $W = W(\lambda)$ substantially deviates from the known law

$$W \propto \beta/\lambda.$$

For the thermal conductivity above 100 W m^{-1} K^{-1}, the value of W changes weakly. For example, as λ increases from 100 to 400 W m^{-1} K^{-1}, the value of W decreases only by 27 %, i.e., in this region the coefficient of thermal expansion plays a great role in the choice of the material for a cooled optical elements. Our analysis also showed that a proper choice of a coolant is no less important.

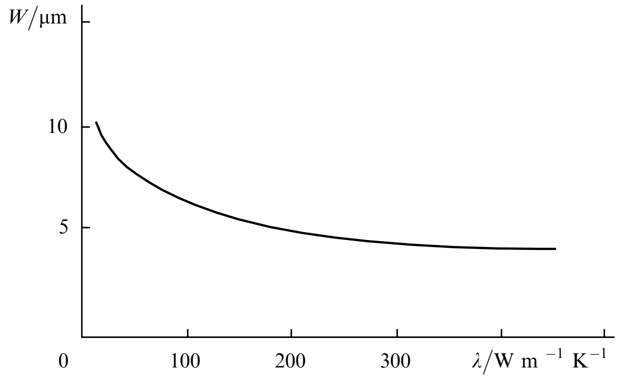

Figure 1. Dependence of the thermal distortions of the reflecting surface on the thermal conductivity of the material of a cooled optical element.

To elucidate this dependence, consider an optical element consisting of a thin reflecting plate of thickness h and of a massive substrate, between which a heat exchanger is located. The thermal parameters of the heat exchanger are described by the thermal conductivity λ_p, the bulk heat-transfer coefficient α_v, and the porosity P. We assume that the heat is concentrated only in the reflecting plane and in the adjacent part of the heat exchanger, the substrate of the mirror remaining thermally insulated.

The reflecting surface is distorted in this case due to the thermal expansion of the reflecting plate, where the temperature is distributed linearly, and of the heated part of the heat exchanger, where the temperature is distributed exponentially. Taking into account these assumptions, the deformation of the reflecting surface has the form

$$W_n \approx \beta\left[\frac{1}{\alpha_v} + \frac{h}{(\alpha_v\lambda_p)^{1/2}} + \frac{h^2}{2\lambda}\right]. \tag{1}$$

The first term in this expression corresponds to the deformation of the cooled layer, and the second and third terms – to the expansion of the reflecting plate.

By using the analytic solution for the bending of the optical element, we can show that the bending strain is

$$W_b \approx \beta\frac{h}{(\alpha_v\lambda_p)^{1/2}}. \tag{2}$$

We represent the total deformation of the optical surface in the form

$$W = W_n + W_b. \tag{3}$$

Let us introduce the dimensionless parameter

$$k = \frac{h}{2}\left(\frac{\alpha_v}{\lambda_p}\right)^{1/2}.$$

The thermal conductivity λ_p of a porous medium can be expressed in terms of the porosity and thermal conductivity of the initial material:

$$\lambda_p = \lambda(1 - P).$$

Then,

$$W \approx \frac{\beta}{\alpha_v}[1 + 4k + 2k^2(1 - P)]. \tag{4}$$

Table 1. Parameters of some materials proposed for manufacturing optical elements.

Material	$\lambda/$ W m $^{-1}$ K^{-1}	$\beta/$ 10^6 K^{-1}	$E/$ 10^{-10} N m^{-2}	$\sigma_T/$ 10^{-7} N m^{-2}	$\rho/$ 10^{-3} kg m^{-3}	ε_T/μm	$\frac{E}{\rho}/$ 10^{-7} m^2 s^{-2}	$\Delta T_{\max}/$K	$\frac{\sigma_T}{E\beta\Delta T_{\max}}/$ 10^{-3}
Deformed copper	400	17.4	11.2	6.85	8.93	1.02	1.25	12.5	2.8
Tungsten	160	4.5	40	29.4	19.1	0.36	2.1	22.2	9.3
Molybdenum	130	5.2	31	10.8	9.01	0.40	3.4	19.7	2.7
Stainless steel	20	16.6	20.0	23.5	7.85	1.9	2.55	79.9	0.87
Nickel	92	13.3	20.2	20.5	8.90	1.13	2.27	26.0	2.9
Aluminium	211	24.5	6.85	6.44	2.70	1.77	2.54	17.2	2.2
Titanium	15.5	8.5	10.9	7.5	4.54	1.06	2.42	101	0.8
Beryllium	182	13.7	33	–	1.85	1.03	17.8	18.4	–
Invar	11	1.6	14.7	–	8.00	0.22	1.84	145	8.00
Silicon	140	3.0	11.3	–	2.42	0.24	4.67	21.5	–
Silicon carbide	110	3.3	39.2	–	3.2	0.28	12.2	25	–

The thermal conductivity enters (4) implicitly via the parameter k. The bulk heat-transfer coefficient takes into account the coolant properties and the heat-exchanger design. Therefore, the stability parameter of cooled optical elements depends not only on the thermal conductivity and the coefficient of thermal expansion of the material. The design of the optical element and the coolant parameters are also important.

It follows from expression (4) that, as the reflecting plate thickness decreases, the stability parameter becomes independent of the material heat conductivity and is determined at $h = 0$ only by the ratio of the coefficient of thermal expansion of the material to the bulk heat-transfer coefficient

$$W \approx \beta/\alpha_v .$$

For large values of k, the stability parameter becomes proportional to the known ratio β/λ.

Table 1 presents the comparative parameters of some materials proposed for manufacturing optical elements. The light-flux density and the design of the optical element are chosen so that the thermal deformation ε_T of the reflecting surface within a light spot for copper optical elements with a

Figure 2. Meeting of the Editorial Board of the Journal of Experimental and Theoretical Physics (1973). From left to right: Z.N. Bunakova, E.M. Lifshits, A.M. Prokhorov, M.A. Leontovich, P.L. Kapitsa, E.L. Andronikashvili, V.P. Dzhelepov.

microchannel cooling system is close to 1 μm. The choice of a proper material for manufacturing optical laser elements depends on their functions. In addition, Table 1 presents the bending E/ρ caused by the own weight, the maximum temperature $\Delta T_{\max}$ on the reflecting surface for the light load and the optical-element design specified above, as well as the heat flow density $\sigma_T/(E\beta\Delta T_{\max})$ (σ_T is the yield strength of the optical-element material).

Small-size optical elements, which are used in small-apertures optical paths with a high light-flux density, operate under the conditions of intense heat exchange, and considerable temperature drops are produced in the near-surface region. In this case, materials based on refractory metals such as tungsten and molybdenum are most suitable.

One can see from Table 1 that thermoelastic deformations of the reflecting surface of the optical elements of mirrors made of tungsten and molybdenum are ~ 2.5 times lower than deformation of copper mirrors. In addition, due to a high yield strength, tungsten withstands higher heat-flow densities than molybdenum and copper (Table 1).

The optical elements of laser technological complexes used for light focusing are, as a rule, placed in wide-aperture optical paths. The radiation power densities in this case are low (the integrated power of the beam being preserved) and the temperature of the reflecting surface is an order of magnitude lower than that for the cavity elements subjected to high power densities. This permits the fabrication of such optical elements from invar, which retains its physicomechanical properties only within a certain temperature interval, close to room temperature [7]. Promising materials for manufacturing such optical elements are also silicon, silicon carbide, and materials based on their composition [8, 9].

Therefore, the thermal stability of cooled optical elements for high-power technological complexes depends substantially on the coolant parameters, which along with the heat conduction, the coefficient of thermal expansion, and the heat capacity of materials determine to a great extent the thermal deformations of cooled optical elements.

References

1. Apollonov V.V., Barchukov A.I., Karlov N.V., et al. *Pis'ma Zh. Tekh. Fiz.*, **1**, 522 (1975).
2. Tebo A. *Laser Focus,* **6**, 72 (1988).
3. Ratmann C.L., Mann J.H., Nordberg M.F. *Appl. Opt.*, **7**, 819 (1968).
4. Rodkevich G.V., Robachevskaya V.I. *Opt. Mekh. Prom-st*, **9**, 3 (1977).
5. Apollonov V.V., Prokhorov A.M., Khomich V.Yu., Chetkin S.A. *Kvantovaya Elektron.*, **8**, 2208 (1981) [*Sov. J. Quantum Electron.*, **11**, 1344 (1981)].
6. Maksutov D.D. *Manufacturing and Investigation of Astronomical Optics* (Moscow: Nauka, 1984).
7. Apollonov V.V., Prokhorov A.A., Shmakov V.A., et al. *Pis'ma Zh. Tekh. Fiz.*, **16**, 79 (1990).
8. Apollonov V.V., Gartman M.V., Shmakov V.A., et al. *Pis'ma Zh. Tekh. Fiz.*, **17**, 40 (1991).
9. Apollonov V.V., Babayants G.I., Shmakov V.A., et al. *Pis'ma Zh. Tekh. Fiz.*, **16**, 83 (1990).