CONTROL OF LASER RADIATION PARAMETERS

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On the possibility of high-frequency modulation of laser radiation by using a deformable mirror

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Abstract. **The results of experimental studies of a cooled deformable mirror with a controllable curvature of the reflecting surface in the frequency range from 0 to 40 kHz are presented. The original method is used for measuring the amplitude- and phase-frequency characteristics of the mirror. The dependences of the reflecting surface deformation on the control voltage are obtained at different fixed frequencies near resonances. It is found that the nonlinearity of these dependences is caused by the shift of the resonance frequencies of the mirror with increasing the control voltage amplitude. The parameters of the mirror such as the linewidth, *Q* and damping factors, and peak sensitivity are studied at the 4.69-kHz fundamental and 37.2-KHz high-frequency resonances. It is found that upon the shift of resonance frequencies, the mirror *Q* factor and its peak sensitivity are independent of the control voltage amplitude. The high-frequency modulation depth of laser radiation that can be obtained with such intracavity mirrors is estimated from the results obtained.**

Keywords: *laser radiation modulation, curvature-controlled deformable mirrors, resonance frequencies.*

1. Introduction: Repetitively pulsed intracavity laser radiation modulation

The repetitively pulsed regime of continuously pumped lasers considerably extends their technological and scientific applications. For example, a processing complex based on a standard moderate-power (several kilowatt) cw CO_2 laser operating in the repetitively pulsed regime with a pulse repetition rate variable from 10 to 10^3 Hz acquires new technological possibilities. These are the extension of the assortment of processed materials [1, 2], the realisation of new technological operations [3], the improvement of the processing quality and efficiency [2], etc. The high-frequency (tens of kHz) repetitively pulsed regime of high-power (50 – 100 kW) laser systems permits the realisation of qualitatively new effects, for example, to decrease plasma screening during the interaction of radiation with materials, to reduce the thermal defocusing of radiation on long routes, to increase the energy extraction efficiency in wide-aperture lasers, etc. [4, 5].

The repetitively pulsed regime can be obtained in a cw laser by using a deformable intracavity mirror for the laser *Q*-switching. For example, by means of a single-channel deformable mirror with a controllable curvature of the reflecting surface, the low-frequency (up to 400 Hz) repetitively pulsed modulation of moderate-power (1 – 2 kW) lasers was obtained [6]. A deformable membrane mirror was employed to obtain repetitively pulsed radiation from a low-power (200 W) technological Nd : YAG laser with a pulse repetition rate of 250 Hz [7]. The realisation of the low-frequency repetitively pulsed regime in a laser is definitely determined by the ability of a deformable mirror to quench cw lasing, which means that the laser radiation can be modulated in the frequency range from zero to a few kilohertz. In this case, the upper boundary of the frequency range is determined by the frequency of the first resonance of a deformable mirror used in the laser.

As for the high-frequency modulation of radiation by means of the deformable intracavity optics, such experiments have not been performed so far. At the same time, in the moderate-power and especially high-power (above 10 kW) lasers a deformable mirror is almost the only device capable of playing the role of an optical switch because all other modulators contain transmitting elements. Thus, deformable mirrors are of interest from this point of view, at least for the use in high-power lasers.

It is obvious that to obtain and use such high-frequency repetitively pulsed radiation regimes, it is necessary to have at least the reliable information on the high-frequency properties of deformable mirrors. Not only the amplitude- and phase-frequency characteristics (AFC and PFC) are needed in the frequency range under study, but also the dependences of deformations of the reflecting surface on the control voltage at individual fixed frequencies at which laser radiation can be modulated are required. Obviously, this modulation will be more efficient at the resonance frequency of the mirror because in this case the vibration amplitude of its reflecting surface increases. Therefore, the position, amplitude, *Q* factor, and other parameters of high-frequency (tens of kilohertz) resonances of a deformable mirror are of prime interest.

In this paper, we studied cooled bimorph mirrors with a controllable curvature of the reflecting surface in the frequency range 0 – 40 kHz, which were considered earlier

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in detail in papers [8, 9]. The aim of our study is to determine the applicability of these mirrors for the repetitively pulsed modulation of laser radiation. The upper boundary of the frequency range was chosen based on the real requirements to the modulation frequency of 10–50-kW self-injection gas-dynamic CO_2 lasers [5].

2. Experimental

The vibration amplitude and phase of the reflecting surface of deformable piezoelectric mirrors as functions of the control voltage frequency (i.e., AFC and PFC) can be measured by different methods:

(i) by using devices for measuring vibrations, for example, a displacement sensor [9] or a vibrometer [10];

(ii) by using one of the control piezoelectric drives of a deformable mirror as a sensor of displacements of its reflecting surfaces [11];

(iii) by means of a stroboscopic interferometer [10, 12].

The first measurement method assumes contact between the mirror surface and a sensor and hence is undesirable in the case of highly reflecting optics. The second method is also unacceptable in this case because the deformable mirror has a single control element. As for stroboscopic interferometry, we did not use it because the processing of many interferograms obtained in measurements is a rather long and laborious process.

We used in our experiments the well-known dependence of a signal of a photodetector located in the interferometer on the displacement of a mirror in one of the arms of the interferometer [13]. Figure 1 shows the scheme of the setup for studying the frequency properties of a deformable mirror with a controllable curvature of the reflecting surface. It consists of a Michelson interferometer with plane reference mirror (*6*) in one of the arms and deformable mirror (*7*) in another arm. A laser beam of diameter 15 mm is formed by optical elements (*2*)–(*4*). The beam incident on beamsplitter (*5*) is split into two – the reference beam [reflected from mirror (*6*)] and the object beam [reflected from controllable mirror (*7*)] which interfere in the measuring arm of the optical system. The light intensity at the centre of the interference pattern is [14]

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\varphi, \quad (1)$$

where I_1 and I_2 are the intensities of interfering beams and φ is the phase difference of the reference and object waves. When a plane object mirror is displaced along the optical axis by ξ, the phase difference is

$$\varphi = 2k\Delta l = 2k(\Delta l_0 + \xi), \quad (2)$$

where $k = 2\pi/\lambda$; $\lambda = 632.8$ nm; Δl is the length difference of the reference and object arms of the interferometer; and Δl_0 is the initial difference of the lengths of the arms.

In our case, object mirror (*7*) is not displaced along the optical axis as a whole but is deformed (as shown in Fig. 1) by the control voltage U produced by generator (*13*) and amplifier (*11*). Due to the mirror deformation, the centre of its reflecting surface is displaced along the optical axis. Therefore, expression (2) remains valid if the light beams only near the optical axis are considered. This was achieved by means of 2.7-mm aperture (*8*) placed in the measurement arm of the interferometer. Thus, we measured the vibration amplitude and phase of the reflecting surface of a deformable mirror by the displacement of its centre within the visually controlled adjustment error of the optical system.

Let us assume that the interferometer is initially adjusted so that

$$\Delta l_0 = n\lambda/2 + \lambda/4, \ n = 0, 1, 2, \ldots, \quad (3)$$

and initially plane (for $U = 0$) mirror (*7*) is deformed under the action of the control voltage U so that the centre of its reflecting surface is displaced by the distance H_c. Assuming that $\xi = H_c(U)$ in (2) and taking (1) and (3) into account, we write the light intensity I on photodetector (*9*) in the form

$$I = I_1 + I_2 - 2\sqrt{I_1 I_2}\cos(2kH_c). \quad (4)$$

For interfering beams of the equal intensities ($I_1 = I_2$), we have

$$I = 2I_1[1 - \cos(2kH_c)]. \quad (5)$$

In experiments, the harmonic control voltage

$$U = U_0\sin(2\pi ft) \quad (6)$$

with the amplitude U_0 and frequency f, which was controlled with oscilloscope (*14*) and frequency meter (*15*), was applied to deformable mirror (*7*). The output signal of photodetector (*9*) operating in the diode regime was fed to the second channel of oscilloscope (*14*). Taking into account that the voltage across the photodiode is

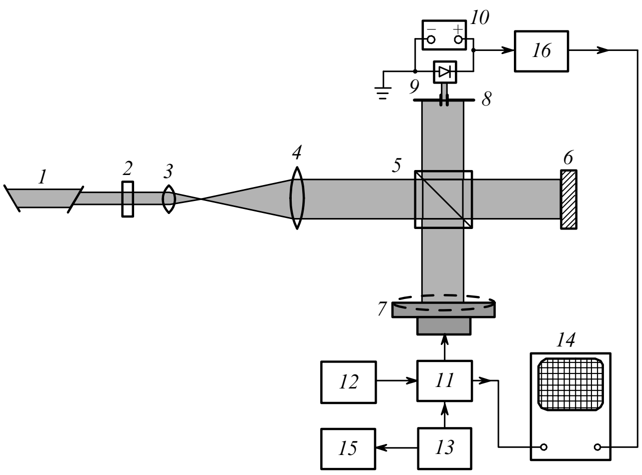

Figure 1. Scheme of the experimental setup: (*1*) LGN-223 laser ($\lambda = 632.8$ nm, the beam diameter is 1 mm); (*2*) attenuating filter; (*3, 4*) lenses; (*5*) beamsplitter; (*6*) reference mirror; (*7*) deformable mirror; (*8*) 2.7-mm aperture; (*9*) FD-256 photodiode; (*10*) power source; (*11*) amplifier; (*12*) power unit; (*13*) standard signal generator; (*14*) Tektronix THS710A double-beam oscilloscope; (*15*) F5041 frequency meter-chronometer; (*16*) U2-11 selective amplifier.

proportional to I and using (5) and (6), we represent the variable component U_r of the photodetector signal in the form

$$U_r = U_n \cos\left[\pi \frac{H_c(U_0;f)}{\lambda/4}\right], \quad (7)$$

where U_n is the proportionality coefficient determined by the rated output power of laser (*1*) and photosensitivity of photodiode (*9*).

Comparison of (6) and (7) shows that the control voltage U on the deformable mirror (and, hence, H_c) changes for the time $T/2 = 1/(2f)$ from a minimum to maximum. Simultaneously, the output signal U_r of the photodetector changes for the same time $T/2$ by a factor of $2N$ from a minimum to maximum, where $N = H_c/(\lambda/4)$. Thus, by measuring N experimentally, we can easily calculate the value H_c corresponding to the amplitude U_0 of the control voltage and its frequency f, thereby obtaining the AFC $H_c(f)$ for the deformable mirror.

By comparing oscillograms $U_r(t)$ and $U(t)$ (Fig. 2), we can calculate the phase shift Θ between the vibrations of the reflecting surface and control voltage, thereby obtaining the PFC $\Theta(f)$ of the deformable mirror. Note that if the initial condition (3) is not fulfilled, the amplitudes of local extrema in the signal $U_r(t)$ are different (shown by the arrows in Fig. 2b) and these amplitudes are equal when this condition is fulfilled. In addition, signals $U_r(t)$ and $U(t)$ have a slight initial phase shift

$$\Theta_0 = \arctan\frac{4\eta}{3\pi} \quad (8)$$

caused by the electromechanical hysteresis η of the deformable mirror [10]. For the mirror used in our experiments, $\eta = 10.2\,\%$, and, therefore, the output signal $U_r(t)$ of a photodiode in the quasi-static regime is delayed with respect to the control voltage $U(t)$ by the value $\Theta_0 = 2.5°$.

3. AFC and PFC of a cooled bimorph mirror with a controllable curvature of the reflecting surface

We studied the frequency characteristics of the mirror for the control harmonic voltage amplitudes $U_0 = 2 - 28$ V.

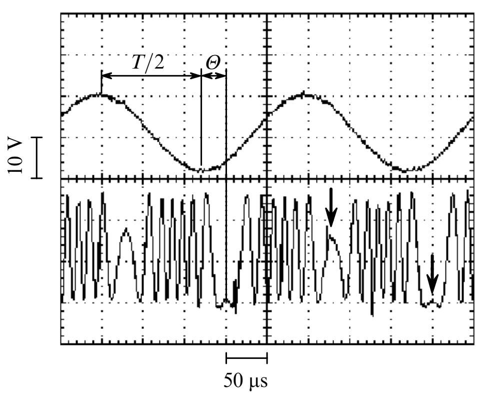

Figure 2. Oscillograms of the control voltage U_0 of a deformable mirror (a) and photodiode signal U_r (b). The scale division is presented for the control voltage oscillogram.

Figure 2 illustrates the determination of the values of N and Θ required for the construction of the AFC and PFC of the mirror. For example, for $U_0 = 10$ V, $f = 4021$ Hz, and $T = 248.7$ μs, we have $\Theta = -0.747$ rad and $2N = 12.8$.

Figure 3 presents the experimental data obtained for $U_0 = 12$ V; similar characteristics were obtained for other control voltages. One can see that the AFC of the mirror in the frequency range under study has two distinct resonance peaks at 4.7 and 38 kHz. After passing through each of these peaks, the vibration phase of the reflecting surface shifts by π radian

$$\Theta(f_{res} + \Delta f) - \Theta(f_{res} - \Delta f) \approx -\pi. \quad (9)$$

In this case, we have directly at the resonance frequency

$$\Theta(f_{res}) \approx \Theta(f_{res} - \Delta f) - \pi/2, \quad (10)$$

as should be the case according to the theory [14]. Here, Δf is a detuning from the resonance frequency f_{res} within the half-width of the resonance peak. A simultaneous graphical processing of the AFC and PFC gave the refined values of the resonance frequencies of the deformable mirror $f_{res1} = 4.69 \pm 0.05$ kHz and $f_{res2} = 37.2 \pm 0.5$ kHz. The corresponding points are shown by rhombs in Fig. 3b. Therefore, the resonance peak observed at a frequency of 37.2 kHz (high-frequency resonance) allows the use of this mirror for high-frequency repetitively pulsed modulation of laser radiation.

Both resonance frequencies f_{res1} and f_{res2} of the mirror correspond to its radial eigenmodes, which depend only on the radial but not angular coordinate (Fig. 4). This follows from the axial symmetry of the mirror construction, which has a single circular control electrode whose centre coincides with the symmetry axis. A more detailed quantitative

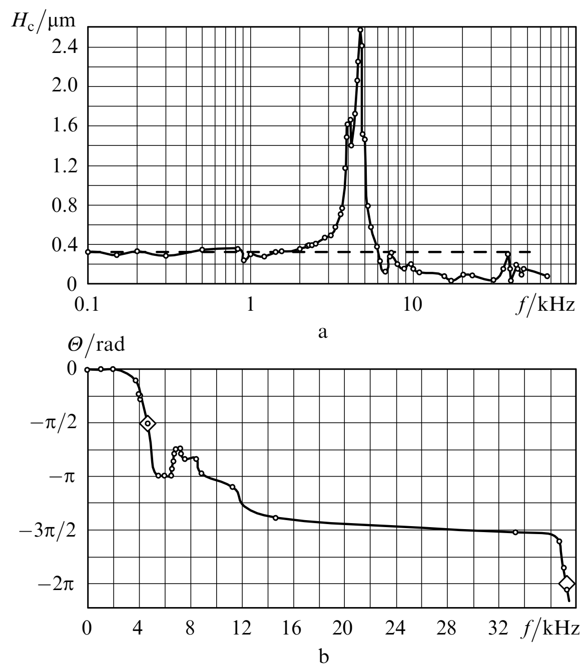

Figure 3. AFC (a) and PFC (b) of a cooled bimorph mirror; the dashed straight line shows the average value of H_c in the quasi-static regime; the rhombs on the PFC are the points of the resonance.

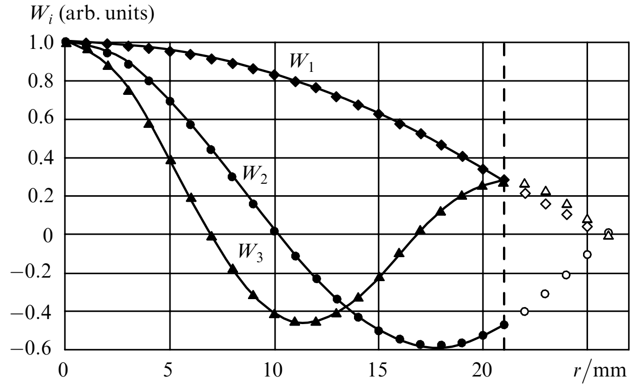

Figure 4. Radial eigenmodes $W_{\rm i}$ of a cooled bimorph mirror with a controllable curvature of the reflecting surface. The dashed straight line shows the boundary of the light aperture.

comparison of the experimental and theoretical data makes no sense because neither of the known mathematical models can describe adequately a real mirror [15].

It follows from Fig. 3 that, despite a similar behaviour of the PFC at the two resonance frequencies, the vibration amplitudes of the reflecting surface at these frequencies are substantially different: $H_{\rm c}(f_{\rm res1})/H_{\rm c}(f_{\rm res2}) = 8.7$. This is explained by the fact that the conditions of spatial 'phase matching' (i.e., the correspondence of the external action distribution to the form of the vibrational eigenmodes of the system [16]) are perfectly fulfilled only for the first radial mode of the mirror, and therefore the maximum resonance effect is achieved at the first resonance frequency corresponding to this mode.

Apart from the resonance peaks considered above, the AFC has a local maximum at a frequency of 4.1 kHz, which is related to the deformable mirror design. In addition, other local extrema also exist, in particular, a minimum at 6.7 kHz (the corresponding phase shift is $\Delta\Theta = \pi/4$ rad) and a maximum at 7.3 kHz ($\Delta\Theta \approx \pi/8$ rad). We assume that these extrema are observed in experiments for the following reasons. A real mirror inevitably has some deviations from the symmetrical construction, which appear during manufacturing of its elements and their assembling. This results in the appearance of the eigenfrequencies of the mirror corresponding to the angular eigenmodes whose vibration amplitude exactly at the centre of the reflecting surface is zero. Therefore, when the AFC is measured by the centre displacement at the eigenfrequencies corresponding to the angular modes, no extrema should be observed. At the same time, they should appear in the AFC even upon a small deviation of the measurement point from the mirror centre, for example, due to an inaccurate adjustment of the optical system. It seems that this occurred in our experiments because the coincidence of the centre of mirror (*7*) and aperture (*8*) (see Fig. 1) with the laser beam axis was controlled only visually.

Note in conclusion that the AFC also has other inhomogeneities in the range 8 – 30 kHz; in this case, the PFC continuously changes in the frequency range from $-7\pi/8$ to $-3\pi/2$. This variation in $\Theta(f)$ can be explained by the presence of the mirror eigenfrequencies in this frequency range. The amplitude of 'resonances' related to these frequencies is so small that they are observed on the AFC as weak inhomogeneities, whose value lies within the experimental error (see Fig. 3a).

4. Resonance properties of a deformable mirror

Analysis of the AFCs obtained near the resonance frequencies allows one to determine a number of parameters characterising a deformable mirror as a vibrating system. One of these parameters is the Q factor, which is in the case of a multimode vibrating system with the resonance frequencies $f_{{\rm res}i}$ has the form [16]

$$\frac{1}{Q} = \sum_i \frac{1}{Q_i}, \tag{11}$$

$$Q_i = \frac{f_{{\rm res}i}}{\Delta f_i}, \tag{12}$$

where Δf_i is the width of the corresponding resonance peak at the $\sqrt{2}$ level. The graphical processing of the experimental results showed that $\Delta f_1 = 0.4 \pm 0.1$ kHz for the fundamental resonance of the deformable mirror and, hence, $Q_1 = 12 \pm 3$; for the high-frequency resonance, $\Delta f_2 = 2 \pm 1$ kHz and $Q_2 = 20 \pm 10$. The large error in the latter case (50 %) is explained by a small number of points on the resonance curve (no more than five) and a large error in the frequency measurement in this range. One can see that the obtained values are of the order of magnitude of Q factors of radio engineering oscillatory circuits, for which $Q \sim 10 - 10^2$ [16].

By using (11) and neglecting other local extrema of the AFC, we obtain the resulting Q factor of the deformable mirror $Q = 8 \pm 3$. It is known [16] that the amplitude of forced oscillations of an oscillator excited at the resonance frequency is Q times greater than that in the quasi-static case for $f_{\rm qst} \ll f_{\rm res}$. The AFC obtained for the fundamental resonance gives the ratio $H_{\rm c}(f_{\rm res1})/H_{\rm c}(f_{\rm qst}) = 8 \pm 1$, where $H_{\rm c}(f_{\rm qst})$ is the values averaged over five measurements in the frequency range 100 – 500 Hz (see Fig. 3a). For the high-frequency resonance, the ratio $H_{\rm c}(f_{\rm res2})/H_{\rm c}(f_{\rm qst}) = 7.5$ proved to be understated because $H_{\rm c}(f_{\rm qst})$ is the experimental value obtained for $f = 31$ kHz. We see that the Q factors of the deformable mirror obtained by different methods for different resonances are in good agreement despite a high measurement error in some cases.

By using the results obtained, we determine the damping factors α_i of the individual modes $W_i(r)$ of a deformable mirror for weakly decaying vibrations of its reflecting surface

$$w(r,t) = \sum_i \exp(-\alpha_i t) W_i(r) \cos(\omega_{0i} t). \tag{13}$$

Here, w is the form of the reflecting surface of the mirror;

$$\omega_{0i} = 2\pi f_{0i} = \left(\omega_{{\rm res}i}^2 + \alpha_i^2\right)^{1/2} = \left(\Omega_{0i}^2 - \alpha_i^2\right)^{1/2} \tag{14}$$

are the cyclic eigenfrequencies of the mirror as a dissipative vibrating system [14]; $\Omega_{0i} = 2\pi F_{0i}$ are the cyclic frequencies of its free vibrations in the absence of friction; and $\omega_{{\rm res}i} = 2\pi f_{{\rm res}i}$. From the definition of α [16] and expression (12), we obtain

$$\alpha_i = \frac{\pi f_{{\rm res}i}}{Q_i} = \pi \Delta f_i, \tag{15}$$

which gives for the fundamental mode of the mirror $\alpha_1 = (1.3 \pm 0.3) \times 10^3\ \text{s}^{-1}$ and $\alpha_2 = (6 \pm 3) \times 10^3\ \text{s}^{-1}$ for the high-frequency mode. It can be easily verified that for such damping factors, the frequencies f_{0i} and F_{0i} virtually coincide with the corresponding resonance frequencies $f_{\text{res}i}$ of the deformable mirror taking into account the errors indicated for the latter. Therefore, we can use resonance frequencies $\omega_{\text{res}i}$ instead of the eigenfrequencies ω_{0i} in (13) to a good approximation.

As expected, the obtained value of α_1 is substantially lower than α_2, and, hence, the decaying vibrations at the fundamental resonance frequency are more 'long-lived'. In addition, in the case of free vibrations of the reflecting surface, the amplitude of the fundamental mode of the mirror is larger than the amplitude of any other mode. Therefore, from the point of view of the decay time, all the eigenmodes of the deformable mirror in expression (13) can be neglected compared to the fundamental mode, and we can assume that free vibrations of its reflecting surface decay at the frequency $f_{\text{res}1} = 4.69$ kHz. Taking into account the energy dissipation in higher-order modes, we obtain the effective damping factor

$$\alpha = \frac{\pi f_{\text{res}1}}{Q}, \tag{16}$$

which gives $\alpha = (1.8 \pm 0.7) \times 10^3\ \text{s}^{-1}$. Thus, the characteristic decay time τ of free vibrations of the reflecting surface of the mirror at the 1/e level is 0.5 ± 0.2 ms.

5. Consideration of nonlinearity with increasing the control voltage amplitude

The results considered above were obtained in the regime of small vibrations of the reflecting surface of mirrors (for a small control voltage amplitude), i.e., when a vibrating system remains linear [14]. As the control voltage amplitude is increased, a deformable mirror becomes a nonlinear system, so that the parameters presented above change in general. First of all this concerns the resonance frequencies $f_{\text{res}1}$ and $f_{\text{res}2}$ of the mirror.

By comparing AFCs obtained for different voltages, we found the shift of resonance frequencies of the mirror with increasing U_0. The corresponding dependence for the first resonance is presented in Fig. 5. One can see that as the control voltage amplitude increases, the resonance frequency decreases and, therefore, the deformable mirror has a soft quasi-elastic characteristic [14].

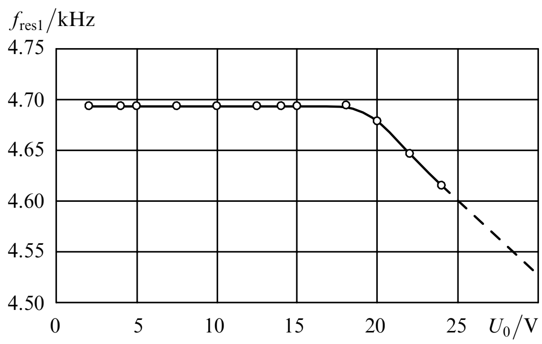

Figure 5. Dependence of the first resonance frequency $f_{\text{res}1}$ of a deformable bimorph mirror on the harmonic control voltage amplitude U_0.

The shift of resonance frequencies of the mirror was distinctly observed in our experiments for the voltage $U_0 \geqslant 20$ V; their shift for $U_0 < 20$ V, if it is exists, is negligible. Therefore, the resonance properties of the deformable mirror begin to change at the control voltage that is rather low compared to its limiting values (−200 and +300 V).

The shift of resonance frequencies with increasing U_0 leads in turn to the nonlinear dependence $H_c(U_0)$ for $f = \text{const}$ at least near the mirror resonances. Recall that the dependence $H_c(U)$ for these mirrors in the static regime is linear at low voltages [8] at least for $U \leqslant 80$ V. In other words, the static sensitivity $K_c = H_c/U$ of the mirror in this range is constant. For convenience of the analysis, we will introduce, similarly to the static sensitivity, the dynamic sensitivity of the deformable mirror at the fixed controlled voltage frequency

$$K_{\text{cf}} = \left.\frac{H_c}{U_0}\right|_{f=\text{const}}. \tag{17}$$

It is convenient to study the dependences $H_c(U_0)$ for $f = \text{const}$ by the example of the fundamental resonance of the mirror, whose amplitude is substantially higher than that of the high-frequency resonance, so that nonlinear effects are more distinct in this case against the background of the experimental error (see Fig. 3a). The corresponding dependences are shown in Fig. 6. One can see that they all are nonlinear in the voltage range under study.

The plots in Fig. 6 can be distinctly divided into two groups according to their type. When $f \geqslant f_{\text{res}1}$ (Fig. 6b), the

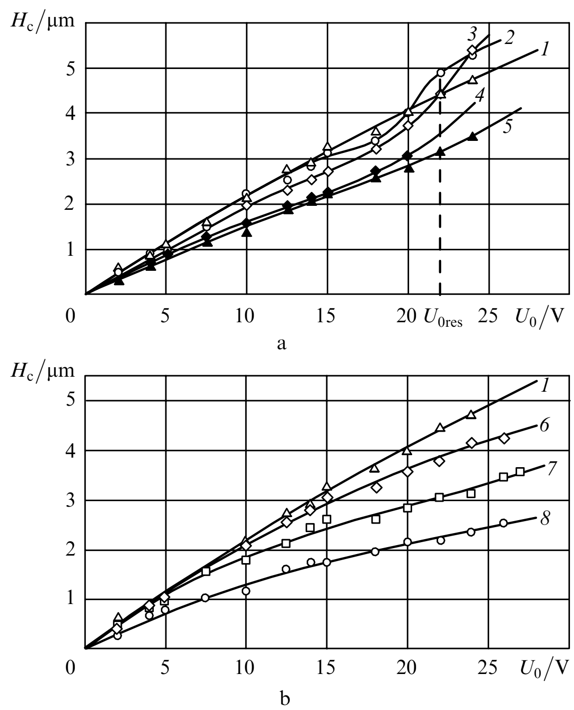

Figure 6. Dependences of the displacement H_c of the centre of the reflecting surface of a deformable mirror on the harmonic control voltage amplitude U_0 for $f \leqslant f_{\text{res}1}$ (a) and $f \geqslant f_{\text{res}1}$ (b) for $f = 4.69$ (*1*), 4.65 (*2*), 4.60 (*3*), 4.55 (*4*), 4.50 (*5*), 4.76 (*6*), 4.86 (*7*) and 5.00 kHz (*8*). The dashed straight line shows the value $U_{0\text{res}} = 22$ V for $f = 4.65$ kHz.

dependence $H_c(U_0)$ increases. Its derivative dH_c/dU_0 and the dynamic sensitivity K_{cf} of the mirror decrease in the range under study. The decrease in K_{cf} and, hence, the nonlinearity of dependences $H_c(U_0)$ are caused by the shift of the resonance frequency f_{res1} of the mirror with increasing U_0. A detailed analysis of dependences $H_c(U_0)$, their derivatives, and $K_{cf}(U_0)$ shows that for $f \geqslant f_{res1}$, the dynamic sensitivity of the mirror decreases down to a stationary value, which is lower, on average, by 40 % than the initial sensitivity.

For $f < f_{res1}$ (Fig. 6a), the dependence $H_c(U_0)$ also increases. However, unlike the previous case, the dynamic sensitivity K_{cf} of the mirror at the frequency f first decreases to a certain level and then increases. The value of K_{cf} increases until the control voltage U_{0res} achieves the value at which the resonance frequency f_{res1} exactly coincides with the given frequency f: $f_{res1}(U_{0res}) = f$. For example, $U_{0res} = 22$ V for $f = 4.65$ kHz in Fig. 6a. As follows from Fig. 5, for $U_0 = 22$ V, the value of f_{res1} is precisely 4.65 kHz. As U_0 is further increased, the dynamic sensitivity K_{cf} again decreases.

As the resonance frequency of the mirror shifts with increasing the control voltage amplitude, the maximum deformations of the reflecting surface at different U_0 are achieved obviously at different frequencies. Taking into account the nonlinear dependence $H_c(U_0)$ for $f =$ const, it is interesting to see how the amplitude of the resonance peak $H_{c\,res} = H_c(f_{res})$ changes with its shift with increasing U_0. Figure 7 presents the dependences $H_{c\,res}(U_0)$ for the fundamental and high-frequency resonances of the deformable mirror. One can see that both these dependences are absolutely linear, so that the resonance (peak) sensitivities $K_{c\,res} = H_{c\,res}/U_0$ of the mirror remain constant in both cases, at least in the range studied.

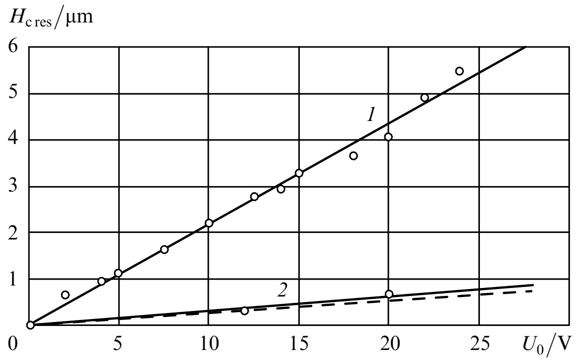

Figure 7. Dependences of the resonance peak amplitude $H_{c\,res}$ on the control voltage amplitude U_0 for a cooled bimorph mirror: (*1*) fundamental resonance; (*2*) high-frequency resonance. The dashed straight line shows the dependence $H_c(U_0)$ in the quasi-static regime.

Because the static sensitivity of the mirror at low voltages is constant, this result means that the ratio $H_{c\,res}/H_c(f_{qst})$ is independent of U_0 (we assume that the sensitivity of mirrors is the same in the static and quasi-static regimes). This means that, despite the shift of the resonance frequencies, the Q factor of the deformable mirror as a multimode vibrating system remains invariable with increasing U_0. Taking expression (11) into account, we can assume that this conclusion is also valid for both fundamental and high-frequency resonances of the mirror because all the dependences for them coincide qualitatively, being different only quantitatively. Therefore, the Q factor of resonances peaks is preserved with increasing the control voltage amplitude: $Q_i =$ const.

It follows from this result and expression (12) that the width Δf_i of each resonance peak of the deformable mirror decreases with increasing U_0. Taking expression (15) into account, this means that the damping factors α_i of individual vibrational modes decrease. In this case, the dependences $\Delta f_i(U_0)$ and $\alpha_i(U_0)$ for each resonance qualitatively coincide with $f_{res\,i}(U_0)$. The resulting damping factor α also decreases with increasing U_0, the dependences $\alpha(U_0)$ and f_{res1} being different only quantitatively [as follows from expression (16)].

6. Analysis of the efficiency of high-frequency laser radiation modulation

Let us estimate the depth of repetitively pulsed radiation modulation by using the intracavity mirror at the high-frequency resonance. Note that we will not consider here lasing processes typical for the Q-switching method. These processes are well studied and were considered in many papers (see, for example, [7, 17]).

It follows from Fig. 3a that the deformation amplitudes of the mirror at the high-frequency resonance and in the static regime (for $f \to 0$) are the same, at least within the experimental error. The case in point is, of course, the centre of the reflecting surface of the mirror, where the mirror deformations are maximal for any radial mode (see Fig. 4). Therefore, the peak sensitivity of the mirror at the high-frequency resonance (i.e., taking the shift f_{res2} into account) coincides with the static sensitivity (Fig. 7). Thus, if the deformable mirror provides the quenching of generation in a laser in the static regime, then the radiation of this laser operating at the high-frequency resonance, taking into account its shift, will be modulated with the modulation coefficient equal to 100 % [18]. Such a result can be expected, for example, for technological Garpun-2000 and Haber-1A stable-resonator CO_2 lasers, in which lasing was quenched upon a static control of a similar deformable mirror [6].

If deformations of a mirror in the static regime are insufficient to quench lasing completely, the output power of the laser will decrease not to zero but to a residual power P_r, which means that the modulation coefficient m at the high-frequency resonance will be lower than 100 %. It can be estimated as

$$m = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} = \frac{P_{rate} - P_r}{P_{rate} + P_r}, \qquad (18)$$

where P_{max} and P_{min} are the maximum and minimum output powers of repetitively pulsed laser radiation and P_{rate} is the rated cw power of the laser.

Taking into account the shape of vibrations of the reflecting surface of a mirror at the high-frequency resonance gives a large value of the modulation coefficient of radiation. Indeed, the mirror deformations in static and quasi-static regimes and near the first resonance corresponding to the fundamental eigenmode are parabolic [8] (see Fig. 4). At the same time, near the high-frequency resonance corresponding to a higher eigenmode, the mirror deformations have a more complicated spatial shape. When an intracavity mirror is used, these deformations introduce phase distortions into the laser cavity, resulting in a decrease in its output power. It is known [13, 19, 20] that more complicated spatial phase distortions cause a greater decrease in the output laser power than less complicated phase distortions. This leads directly to the two conclusions:

(i) The radiation modulation coefficient at the high-frequency resonance will be definitely greater than that in the quasi-static regime, all other factors being the same, i.e., equality (18) passes to the strict inequality

$$m > \frac{P_{\rm rate} - P_{\rm r}}{P_{\rm rate} + P_{\rm r}}. \qquad (19)$$

(ii) The radiation modulation coefficient at the high-frequency resonance equal to the quasi-static modulation coefficient will be achieved at a lower control voltage of the mirror.

As mentioned in section 3, the spatial 'phase-matching' conditions for the high-frequency resonance of the mirror are not fulfilled; only the conditions of temporal, i.e., frequency phase-matching being fulfilled. In other words, the spatial distribution of a driving force (the control voltage) does not correspond to the shape of vibrations of the reflecting surface at the high-frequency resonance, i.e., to a particular eigenmode of the mirror. If these conditions are fulfilled, the vibration amplitude at the high-frequency resonance will increase, resulting in the increase in the coefficient of intracavity high-frequency modulation of laser radiation. In the case of a bimorph deformable mirror, the spatial matching between the control voltage and a radial high-frequency mode can be achieved quite simply by using an additional ring electrode for the second mode or several such electrodes for higher modes. Therefore, a slight modification of the mirror allows one not only to increase the amplitude of the resonance at a frequency of 37.2 kHz (neglecting its shift) but to pass, generally speaking, to the next high-frequency resonances corresponding to the higher-order radial modes. The latter means that laser radiation can be modulated at higher frequencies, at least above 40 kHz.

7. Conclusions

The results obtained in the paper permit the use of the deformable mirrors already now for the efficient high-frequency modulation of laser radiation at frequencies of the order of 37 kHz. First of all, this concerns moderate-power technological CO_2 lasers with standard stable resonators. A comparative analysis of the static and resonance characteristics of deformable mirrors used in the paper makes it possible to estimate the radiation modulation depth at any frequencies for any optical schemes of laser resonators. From the practical point of view, the main technical difficulty concerns the control electronics because a higher-power equipment is required when high modulation frequencies are used, the required equipment power being proportional to the modulation frequency.

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