SELECTION OF THE WAVELENGTH FOR INTERFEROMETRIC CONTROL OF AN ADAPTIVE ASTRONOMICAL TELESCOPE WITH A HOLOGRAM STRUCTURE ON ITS PRIMARY MIRROR SURFACE

V.V. Anishchenko, S.N. Koreshev, V.A. Parfenov, A.G. Seregin, and V.I. Sidorov

All–Russian Scientific Center at S.I. Vavilov State Optical Institute, St. Petersburg
Received October 10, 1993

This paper deals with the problem on choosing the proper wavelength for a wave–front sensor involving an internal laser source and hologram structure on the surface of the primary mirror of a telescope. Some results of dimensional calculations for the optical arrangement of recording of the hologram structure are presented. As a result, a conclusion is drawn on the possibility of reducing the size of an optical setup for making this structure by increasing the operation wavelength of the control channel of a telescope.

A problem to create the large–scale orbital telescope predetermines a necessity to develop a system controlling of running shape of primary mirror (PM) surface and being included in the telescope. One of possible realization of such a system is based on the use of wave–front sensor (WFS) with an internal laser source and hologram structure (HS) on the PM surface.[1,2] In that case the telescope control channel can be described with the use of a block–diagram drawing in Fig. 1. It consists of the PM with HS *1*, secondary mirror (SM) *2*, laser source *3*, acousto–optical frequency modulator (AOFM) *4*, heterodyne interferometer with a narrow reference beam (NRB) *5*, and photorecording unit *6*.

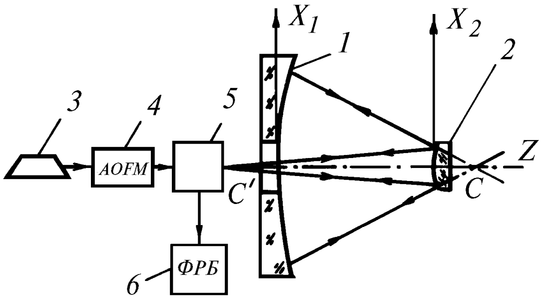

FIG. 1. Block–diagram of the control channel.

Note, the shown construction of the telescope control channel requires the SM be maintained virtually in an ideal form because deformations of the SM surface can be perceived by the WFS as errors in a shape of the telescope primary mirror.

Qualitative characteristics of the above–mentioned control system on the whole, and a technical opportunity for realization of its separate components are mainly determined by the validity of choice of WFS operating wavelength. To consider the ray paths in WFS the following notations are introduced: C' is the point source of monochromatic radiation incident on SM, C is the virtual image of the source C' which is constructed by the mirror *2* and located at an effective "center of curvature" of PM with HS. The ray beam diverging from the point C is incident on the mirror *1* and converted by its surface and by HS into the ray beam converging to autocollimation points of the primary mirror C and C'. The information about the deformations in the shape of the primary mirror is readout by the use of WFS which receives the referred beam after reflection from the mirrors *1* and *2*.

In the absence of deformations in the surfaces of mirrors *1* and *2* and with the use of physical holography techniques for drawing of hologram structure, the phase distribution for the wave diverging from the point C and diffracted on the referred structure on the surface of mirror *1* can be described by the following way:

$$\nu = \nu_C + D\,\nu_{2-1} + m\,(\nu_o - \nu_r)\,, \qquad (1)$$

where ν_C is the phase distribution corresponding to the aberrationless spherical wave diverging from the point C, $D\,\nu_{2-1}$ is the wave aberration inserted by the secondary mirror into the ray beam reflected by the mirror surface and diverging from the point C', m is the ratio of wavelength of hologram structure reconstruction, equalled to WFS operation wavelength l_k in the considered case, to the length of object wave l_o at the instant of its recording; ν_o and ν_r are the phase distributions for the object and reference waves on the PM surface when recording of the hologram structure.

Allowing for the "dualism" of the reflecting hologram structures,[3] the phase distribution in the wave reflected from the PM surface and converging at the point C' can be represented by the following relation:

$$\nu' = -\,\nu'' = -\,\nu_C - D\,\nu_{2-1} - m\,(\nu_o - \nu_r) \qquad (2)$$

Therefore, the following phase distribution over the PM surface can correspond to an ideal or, aberrationless spherical wave converging at the point C':

$$\nu'' = \nu_C + D\,\nu_{2-1}\,. \qquad (3)$$

Hence, the aberrations of the telescope control channel can be presented in the form

$$D\,W = \nu' - \nu''\,,$$

or, allowing for Eqs. (2) and (3),

$$D\,W = -\,\{2\,\nu_C + 2\,D\,\nu_{2-1} + m\,(\nu_o - \nu_r)\}\,. \qquad (4)$$

0235-6880/93/12 902-05 $02.00

Note, that all the above–mentioned wave–front sources C and C' and also the sources of reference and object waves are aligned on the optical axis of telescope mirrors unit when recording of HS. By taking into account this fact, the wave phase distribution for the ray beam spreading from the point source C on the PM surface can be described correct to a constant by the following expression which is written in the third–order approximation[4]:

$$\nu_C = \frac{2p}{l_c}\left\{\frac{1}{2Z_C}\left(1-\frac{Z_C}{r_1}\right)X_1^2 - \frac{1}{8}\left(\frac{1}{Z_C^3}-\frac{2}{r_1 Z_C^2}+\frac{e_1}{r_1^3}\right)X_1^4\right\}, \quad (5)$$

where Z_C is the distance from the point of C to a vertex of the secondary mirror along the Z axis, moreover, if the point is placed on the right of the mirror vertex, then $Z_C > 0$, if it is placed on the left, then $Z_C < 0$. Here r_1 is the vertex radius of curvature of PM surface; the sign of r_1 is determined by the sign of coordinate Z of the corresponding mirror curvature center; e_1 is the function of eccentricity, it is determined from the equation describing the mirror surface shape as $2rZ = X^2 + eZ^2$. The vertex radius of curvature and eccentricity function of the secondary mirror are characterized further by the parameters r_2 and e_2, respectively.

Let us write down analogous expressions for ν_o and ν_r and substitute them into Eq. (4), then

$$D\,W = -\frac{2p}{l_c}\left\{\left[\frac{1}{Z_C}-\frac{1}{r_1}+\frac{m}{2}\left(\frac{1}{Z_o}-\frac{1}{Z_r}\right)\right]X_1^2 - \right.$$

$$-\frac{X_1}{8}\left[\frac{2}{Z_C^3}-\frac{4}{r_1 Z_C^2}+\frac{2e_1}{r_1^3}+\right.$$

$$\left.\left.+\,m\left(\frac{1}{Z_o^3}-\frac{1}{Z_r^3}-\frac{2}{r_1}\left(\frac{1}{Z_o^2}-\frac{1}{Z_r^2}\right)\right)\right]\right\} - 2\,D\,\nu_{2-1}\,. \quad (6)$$

Having equalled the coefficient for X_1^2 to zero we obtain from Eq. (6) the condition of autocollimation reflection from the mirror *1* with the hologram structure of the ray beam diverging from the point C:

$$\frac{1}{Z_C}-\frac{1}{r_1}+\frac{m}{2}\left(\frac{1}{Z_o}-\frac{1}{Z_r}\right)=0\,. \quad (7)$$

If condition (7) is valid Eq. (6) describing the wave front aberration of the third order in the interferometer *5* is reduced to the form

$$D\,W = -\frac{2p}{l_c}\frac{X_1^4}{8}\left[\frac{2}{Z_C^3}-\frac{4}{r_1 Z_C^2}+\frac{2e_1}{r_1^3}+\right.$$

$$\left.+\,m\left(\frac{1}{Z_o^3}-\frac{2}{r_1 Z_o^2}-\frac{1}{Z_r^3}+\frac{2}{r_1 Z_r^2}\right)\right]-2\,D\,\nu_{2-1}\,; \quad (8)$$

where, taking Eq. (4) into account

$$D\,\nu_{2-1} = \frac{2p}{l_c}S_{2-1}X_1^4\,,$$

$$S_{2-1} = \frac{Z_{C'}^4}{Z_C^4}\frac{1}{4r_2}\left(\frac{1}{Z_C^2}-\frac{2}{r_2 Z_{C'}}+\frac{e_2}{r_2^2}\right). \quad (9)$$

By substituting Eq. (9) into Eq. (8) we obtain the following expression under autocollimation condition (7)

$$D\,W \sim \frac{2p}{l_c}\frac{X_1^4}{8}\left\{\frac{6}{Z_r^2}\left(\frac{1}{r_1}-\frac{1}{Z_C}\right)+\frac{4}{Z_r}\left(\frac{1}{r_1}-\frac{1}{Z_C}\right)\times\right.$$

$$\times\left(\frac{3}{mr_1}-\frac{3}{mZ_C}-\frac{2}{r_1}\right)+\frac{8}{m^2}\left(\frac{1}{r_1}-\frac{1}{Z_C}\right)^3-$$

$$\left.-\frac{8}{mr_1}\left(\frac{1}{r_1}-\frac{1}{Z_C^2}\right)^2+\frac{1}{Z_C^3}-\frac{4}{r_1 Z_C^2}+\frac{2e_1}{r_1^3}-16\,S_{2-1}\right\}. \quad (10)$$

At specified values of Z_C and DW the Eqs. (7) and (10) make it possible to determine such wavelengths of the HS recording and reconstruction as well as such distances from the PM vertex up to the reference and object sources at which the autocollimation path of rays will be realized for preset aberrations (for example, for zero aberrations) in the telescope control channel. Because the values of Z_C, DW, and S_{2-1} are given, as a rule, and the parameters Z_o and Z_r are generally related between each other by the autocollimation condition then as it follows from Eq. (10), there is the only one free parameter m by means of which the values of Z_o and Z_r can be influenced when recording of HS.

Let us consider an effect of the parameter m and, consequently, the wavelength of PM shape control on Z_o and Z_r more attentively. For that let the point C (as it was proposed in Ref. 1) be in the focal plane of PM, i.e., $Z_C = r_1/2$ and the notations $Z_r = R\,r_1$ and $Z_o = O\,r_1$ be introduced. Then from Eqs. (7) and (10) we obtain

$$\frac{1}{R} = \frac{2}{3}+\frac{1}{m}+\frac{0.58}{m}\sqrt{B}\,, \quad (11)$$

$$\frac{1}{O} = \frac{2}{3}-\frac{1}{m}+\frac{0.58}{m}\sqrt{B}\,, \quad (12)$$

$$B = -\,m^3 r_1^3\frac{4\,l_o}{2\,p\,X_1^4}DW + m^2\left(e_1 - 8\,r_1^3 S_{2-1}+\frac{4}{3}\right)-1\,.$$

Note, that only the positive values of parameters R and O are of interest for experience, i.e., it is the case when recording of the hologram structure is carried out by the ray beams diverging from the reference and object sources located on the same side of the primary mirror. For the general case when e_1, S_{2-1} are small and $DW = 0$, the above–indicated relation is satisfied for the sign "+" before the radical and for $m > 1$. In this case the parameter R is virtually independent of on m and the parameter O decreases essentially when m increases. This behavior is illustrated by the curves for R and O as functions of m which are presented in Fig. 2 and calculated for $e_1 = S_{2-1} = DW = 0$.

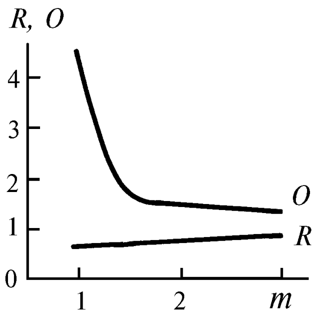

FIG. 2. Parameters R and O as functions of the ratio of the control channel operation wavelength to PM recording wavelength.

The results of analysis carried out make it possible to draw two main conclusions. First, recording of hologram structure on the primary mirror surface at the wavelength being more than operation one of telescope control channel is not possible. Second, it is reasonable to increase the used wavelengths ratio from the point of view of decreasing in the required overall dimensions of recording setup of the holographic structure as well as increasing in the used wavelength ratio. Thus two–fold increasing in the wavelength allows us to reduce a length of the holographic structure recording setup more than by the factor of four, as it follows from Fig. 2. Note, that transition to a greater wavelength, naturally, must not cause a loss in the accuracy of PM shape control. It requires, in its turn, special care to be taken to keep a constant value of minimum deformation dH_1 of PM surface measured by WFS.

To keep a value of this parameter unchanged we use a simplified expression for the sensitivity of interferometric control of photodetector S_s. This relation is obtained by the known equation for the interference bandwidth H_l (Ref. 6) and definition of the limiting phase resolution s_{ph} (Ref. 7). Then the threshold sensitivity is characterized by the following relation:

$$H_l/dH_l = 2\,p/s_{ph}\ , \qquad H_l = l_k/2M\cos a\ , \qquad (13)$$

where l_c is the wavelength in the control channel, a is the angle of incidence of ray on the PM surface at the given point, M is the number of reflections from PM, and H_l is the deviation of PM shape which corresponds to the change in optical path length difference by l_k for the given M and a.

In the considered variant of WFS: $M = 1$, $a = a(X)$, where $d/2 \ll X \ll D/2$, D is the diameter of PM, and d is the diameter of the hole in PM. The angle of incidence a is changeable here, so as autocollimation of the control beam is provided by HS rather than PM surface. In this case the expression for the sensitivity S_s has the form

$$S_s = \frac{4\,p\,M\cos a}{s_{ph}\,l_c}\ , \qquad (14)$$

Equation (14) includes the principle parameters the valid choice of which makes it possible to solve the problem on remaining unchanged the control accuracy allowing for the minimisation criterion for overall dimensions of PM recording scheme. The parameters in the numerator of Eq. (14) are determined by geometry of WFS and independent on the wavelength of radiation. The denominator is an "invariant" relatively to the operation wavelength of control l_c when it is necessary to keep the constant parameter S_s. It means that the change in l_c requires the corresponding change in the parameter s_{ph}.

One of the factors restricting the limiting phase resolution s_{ph} is a value of potentially achievable accuracy of phase measurement s in the recording unit.

Let us evaluate the change in s when the control channel length l_c increases. The use of WFS on the basis of heterodyne interferometer provides forming of two beams of radiation with the frequencies f_1 and f_2 which differ in some fixed value of the difference frequency f_0. According to technical realization the high–stable value f_0 cannot be too low and it is units or tens of kilohertzs in the scheme of interferometer with acousto–optical modulator. That causes the necessity to use the dissector as an input element of recording unit of scanning photodetector of instantaneous operation.

To compare the energy efficiency of the operation wavelength of the control system, we consider a power model of measuring tract. The model includes the laser, AOFM, interferometer, PM with HS, and recording unit (see Fig. 1). As shown in Ref. 8, the value of potentially achievable accuracy of phase measurement s, limited by the shot component of the dark current of photodetector, is determined by the following relation:

$$s = (0.5\,A\sqrt{I_d})\,/\,(P\,K\,S\sqrt{t})\ , \qquad (15)$$

where I_d is the dark current of photodetector, t is the measurement time, P is the light signal power, S is the photodetector sensitivity, K is the contrast of interference pattern, A is the parameter allowing for the laser noise.

The above relation describes the basic exchange relationships between the power of optical signal, measurement time and potentially achievable accuracy of phase–meter. It should be noted that this relation characterizes the recording unit only and does not take into account the sources of errors from other elements of WFS (PM, radiating source, and interferometer).

On the one hand, the change in the operation wavelength causes a change in the photocathode sensitivity S and, on the other hand, a change in the energy efficiency of optical tract h. In this case the power P at the photodetector input equals to $P_l h$, where P_l is the laser radiation power. In its turn, h depends on energy transfer coefficient of individual optical elements included in the interferometer and HS. For example, when changing the wavelength from 0.53 μm to 1.06 μm the sensitivity of dissector photocathode is reduced by an order approximately,[9] while the requirement for an accuracy of phase measurement is doubled with doubling of wavelength as follows from Eq. (14). As is seen from Eq. (15), in this case to keep the constant measurement accuracy of PM deformations, the light signal power of the detector photocathode should be increased about 20–fold keeping the energy efficiency of the other components of WFS optical scheme unchanged.

In this connection we consider the principle requirements imposed on a laser source which would be used in WFS with PM. The power and wavelength of radiation, consumed electrical power, as well as the mass and overall dimension characteristics (they are especially important for orbital telescopes) can be placed into the category of such requirements. Moreover, the presence of hologram structure on the primary mirror of telescope results in unequal arms of the WFS interferometer that leads to additional requirements imposed on the time coherence of a laser.

The He–Ne lasers having the high spatiotemporal coherence and stability of radiation frequency are customary to use in the control systems. However, application of He–Ne lasers to control the mirrors with HS is impossible due to lower radiation power for required weight and dimension characteristics. Moreover, the deficiency of power cannot be compensated by relatively short wavelength of radiation of these lasers.

As for powerful sources of short–wavelength radiation such as ion lasers on the inert gases (Ar, Kr), they cannot be used by reason of high power consumption that causes not only great power emission but, as a result, thermal and erosion distortions of gas–charge tubes. Apart from the exploitation difficulties that leads to the essential reduction in service lifetime of laser.

Allowing for all these facts from our point of view it is more reasonable to use the solid–state laser (SL) combining a possibility for obtaining high–powerful radiation with high efficiency and small dimensions of a source in the space telescope control system. The other essential advantage of SL is practically unlimited service time of an active element.

Of all the SL's the YAG:Nd laser is the most convenient radiating source. The following advantages of this laser should be noted: a possibility for obtaining the powerful coherent radiation with diffraction divergence as well as possibility for operating in the different regimes of lasing (CW, pulsed, and pulsed–periodic). Besides, let us especially note a possibility for creating the compact YAG:Nd lasers with extremely low consumed power and high efficiency in the case of using the laser diode or light diode pumping of an active element.

Successes have recently been achieved in the field of manufacturing methods of semiconductor structures lead to an appearance of high–efficiency compact YAG:Nd lasers with pumping by laser diodes and whose radiation powers are up to 1 kW at the principle wavelength 1.06 μm in the regime of multimode lasing[10] and up to 15 W in the single–frequency regime.[11]

To obtain the short–wave radiation conventionally used for the interferometric control of mirror quality, it is necessary to double the radiation frequency of YAG:Nd laser (l = 0.53 μm). However the frequency doubling leads to essential losses in the output power that testifies good prospects in the use of principle harmonic of YAG:Nd laser radiation in the WFS. To test validity of the exchange relations for the radiation wavelength 1.06 μm we carried out the experiments on revealing the power potentialities of these lasers. We used YAG:Nd lasers with both the diode and lamp pumping allowing us to obtain the highest levels of radiation power.

To obtain radiation with the narrow spectral line and hence with the high time coherence that is important for producing the interferometers with nonzero path length difference in the operation and reference channels, a selection of longitudinal types of laser oscillations is required. Because the YAG:Nd laser is the laser with the homogeneously prolonged line of gain, the single–frequency lasing can be obtained by elimination of spatial inhomogeneity in the electromagnetic field in a resonator by means of creation of the running wave. Such a regime is much more easily implemented in the circular resonators with the Faraday optical shutter.[12] According to this principle the optical arrangements of studied laser resonators were constructed.

In the experiments on determination of the power potentialities of the YAG:Nd lasers with the lamp pumping we used the single–frequency CW laser. The technical solutions developed in Refs. 13 and 14 are taken as the basis of construction of the above laser. An active element was YAG:Nd crystal of 4 mm diameter and 65 mm length. The active element was pumped by the arc krypton lamp of the DNP–4/60 type. The single–frequency lasing with the mean maximum radiation power 4.5 W for the electrical power of pumping 1.8 kW was obtained in the experiments. To compare let us note that the maximum power of single–frequency radiation of the second harmonic (l = 0.53 μm) obtained in the analogous laser scheme is 200 mW (see Ref. 13). These results testify that exchange relations (14) and (15) are satisfied.

To study the power potentialities of the single–frequency YAG:Nd lasers with the semiconductor pumping, a scheme of the single–frequency monolithic ring laser so–called chip–laser with the longitudinal laser diode pumping of an active element was chosen.

The resonator of the chip–laser is formed by the prism active element in which the ray path is set by total internal reflection from the prism faces.[15,16] This sufficiently simplifies the laser construction and, besides, makes it stable to disadjustments. The other advantage of the considered resonator configuration is its compactness.

To pump the active element, the phototypes of GaAlAs–laser diodes with the radiating power 500 mW at the wavelength 807 nm were used in our experiments. The obtained maximum radiation power in the single–frequency regime was 80 mW at the wavelength 1.06 μm. Note, the power level of the chip–laser can be sufficiently increased, for example, up to 15 W in the master–oscillator – amplifier scheme.[11] Hence, in the case of YAG:Nd laser with diode pumping the exchange relations are also satisfied.

The analysis carried out verifies the advisability and good prospects of using the YAG:Nd lasers in WFS of adaptive telescopes with the hologram structure on the primary mirror. In this case the choice of the principle harmonic of radiation of these lasers makes it possible not only to reduce the dimensions of setup for hologram structure recording keeping the absolute accuracy of control of mirror surface shape but to refuse from the frequency doubling of YAG:Nd laser radiation which is inefficient and technically difficult from the point of view of power.

In conclusion the authors thank D.N. Es'kov, B.E. Bonshtedt, and V.I. Podoba for their useful discussions and support.

REFERENCES

1. V.S. Zuev, E.P. Orlov, and V.A. Sautkin, Kvant. Elektron. **2**, No. 1, 92–98 (1975).
2. M.A. Gan, B.A. Ermakov, D.N. Es'kov, et al., Tr. Gos. Opt. Inst. **74**, No. 208, 42–54 (1989).
3. G. Colfield, ed., *Optical Holography* [Russian translation] (Mir, Moscow, 1982), 639 p.
4. P.E. Verboven and S. Lagasse, Appl. Opt. **25**, No. 22, 415 0–4154 (1986).
5. S.T. Bobrov, G.I. Greysukh, and Yu.G. Turkevich, *Optics of Diffraction Elements and Systems* (Mashinostroenie, Leningrad, 1986), 223 p.
6. D. Malakar, ed., *Optical Production Control* (Mashinostroenie, Moscow, 1985), 400 p.
7. H.P. Stahl, SPIE **680**, 29–34 (1986).
8. V.V. Anishchenko and V.I. Sidorov, in: *Abstracts of Reports at All–Union Seminar on Metrology of Laser Measurement Systems,* Part 1, University, Volgograd, p. 52 (1991).

9. *Catalog on Photoelectron Equipment* (All–Union Research Inst. "Elektron", Leningrad, 1990).
10. Laser Focus World, No. 9, 15 (1992).
11. D. Golla, H. Zelmer, W. Shone, et al., Conf. on Laser and E–O., USA Tech. Dig. Set. **11**, 480–482 (1993).
12. A.L. Mikaelyan, Yu.G. Turkov, V.F. Kuprishov, et al., Zh. Eksp. Teor. Fiz. **57**, No. 1(7), 38–41 (1969).
13. S.V. Kruzhalov, V.A. Parfenov, L.N. Pakhomov, et al., Pis'ma Zh. Teor. Fiz. **8**, No. 12, 756–759 (1982).
14. S.V. Kruzhalov, V.A. Parfenov, L.N. Pakhomov, et al., Pis'ma Zh. Teor. Fiz. **54**, No. 10, 2075–2077 (1984).
15. T.J. Kane and R.L. Byer, Opt. Lett. **10**, 65 (1985).
16. D.Z. Garbuzov, V.V. Dedysh, A.V. Kochergin, et al., Izv. Akad. Nauk SSSR, ser. Fizika **54**, No. 12, 2397–2401 (1990).