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Linear conjugate phase-locking of independent single-mode emitters

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Abstract. The problems of the construction of laser systems based on the methods of linear adaptive optics and designed for energy transport over large distances in outer space are analysed. New approaches are proposed to the organisation of the linear phase conjugation of output and beacon-signal radiations. For definite ratios of the beacon-signal (ω_b), heterodyne (ω_h), and power (ω_p) radiations ($\omega_b > \omega_h > \omega_p$ or $\omega_b < \omega_h < \omega_p$), the phase conjugation loop may play simultaneously the role of a precision frequency matching loop. This feature permits the phase locking of independent single-mode laser emitters, including phase locking in the far-field zone, to achieve the modular principle of system design and to generate the wavefront of radiation with a large cross section.

1. Introduction

A key scientific problem in the Lunar Energy Park (LEP) project, proposed by Japanese scientists [1] and designed to utilise the natural resources of the Moon in order to solve the problem of global energy crisis, is the delivery of energy to the Earth. The transport of energy with the aid of laser radiation is considered within the framework of the proposed concept [2]. It is suggested that a rotatable mirror, placed in a geostationary equatorial orbit (Fig. 1), be used to transport radiation to a receiving station located at a particular point on the Earth's surface. Bearing in mind the complexities in the formation of a plane wavefront with a large cross section, the size of the mirror should not differ significantly from that of the lunar emitter.

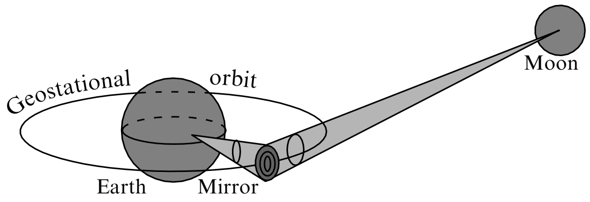

Figure 1. Schematic illustration of energy transport by radiation from the Moon to the Earth through a mirror located on a geostationary equatorial orbit.

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Taking into account the requirement for a high radiation delivery efficiency, the latter factor determines the characteristic size of the lunar-emitter aperture in operation at a specified radiation wavelength. The requirement for a high system efficiency rules out from consideration laser media which are not highly efficient in the generation of powerful cw radiation. It is proposed that a laser system with an active medium based on carbon dioxide be used in the LEP project. Diode-pumped solid-state lasers are being developed rapidly. Lasers of this type exhibit a very high efficiency in the conversion of electrical energy into optical energy, but the experience gained in their construction is as yet insufficient. Nevertheless, bearing in mind the likely usefulness of such lasers and their short wavelength, it is not desirable to exclude them from consideration.

Depending on the permissible losses, the diameter of the lunar emitter should be between 30 and 60 m for radiation at a wavelength of 1.06 μm and from 90 to 180 m for radiation at a wavelength of 10.6 μm. The orbital rotatable mirror should also be of comparable size. It is suggested that the power of the lunar emitter should be 10 MW in the second (demonstration) stage of the project. Further plans of the developers involve both an extensive and an intensive (up to 10 – 30 GW per emitter) development of the system.

In our view, one of the most reliable methods ensuring the viability of the radiation-transport system in outer space is the phase locking of independent single-mode emitters. Hitherto, this method has not found a serious practical application in the optical range because of its great technical complexity and hence the undesirability of its employment in systems with small and moderate cross sections. The aim of the present study is to demonstrate the possibility of the phase locking of independent emitters in order to ensure definite system parameters.

2. Advantages of the methods of linear adaptive optics

The possibility of the formation of wavefronts with a large cross section from the laser-beam signal by employing the methods of nonlinear-optical phase conjugation has been analysed [2]. Two types of system have been considered. The first of these presupposes the use of a telescope with a diffraction structure on the main mirror [3] and of a write – read algorithm [4].

The second type of system for the formation of a wavefront with a large cross section is based directly on the phase conjugation [5] of the beacon radiation. The key problem in the implementation of both systems is the construction of a phase-conjugate mirror able to phase-conjugate simultaneously and coherently the radiation of all the amplifying modules. The attainment of the phase conjugation of cw radiation by a nonlinear-optical method is at present a difficult task backed by little practical experience. A wavefront with a comparatively large cross section may be generated, in particular, also as a result of the passive phase locking of a two-dimensional emitter array [6], but a reasonable limit to the aperture diameter in systems of this kind hardly exceeds appreciably 1 m. The use of phase-locking systems based on linear adaptive optics is therefore a by no means unique approach to the employment of IR cw lasers.

A characteristic feature of the linear devices in adaptive optics [7] is the separation of processes involving the analysis and correction of the spatial distribution of the radiation phase. This separation is the main disadvantage and at the same time the main advantage of linear methods of adaptive optics compared with the nonlinear methods. It is responsible for a considerable technical complication of the apparatus and for the stringent requirements in respect of the precision of the alignment of the optical system, of the spectral parameters of the emitters, and of the temporal characteristics of the correctors. On the other hand, the application of linear adaptive devices possesses a whole series of advantages.

First, such separation of the processes makes it possible to introduce any correction in the simplest manner at the stage involving the generation of signals for the control of the correctors. In particular, in the transport of radiation to a distant moving object the introduction of angular prediction makes it possible to place the laser beam directly on the object. Second, the phase-conjugation procedure presupposes the presence of an ideal reference wavefront. The separation of analysis and correction is responsible for the independence of the power of the output radiation of the reference signal, which makes it possible to ensure the phase conjugation of high-power radiation on the basis of a reference signal of hundreds of milliwatts. The lower the radiation intensity, the easier it is to ensure to ideality of its phase surface.

Third, by virtue of the independence of the power of the output radiation of the signal-wave amplitude, the requirements of linear adaptive systems as regards the intensity of the signal wave are not stringent. As a result, the problem of the suppression of superluminescence is readily solved in the system. The urgency of this problem in nonlinear phase conjugation systems increases strongly with decrease in the input signal and with increase in the output signal. Fourth, the use of linear adaptation gives one much freedom in the development of an optical system for the transport of radiation. The diversity of methods for analysis and correction makes it possible to separate the problems of compensating for distortions of different physical nature, to adopt a modular design of the system, and to select the size of the modules from the standpoint of technical usefulness.

3. Advantages of a system of independent emitters

The problem of the dynamic range of the correctors arises in the construction of linear adaptive systems [7, 8] for high-power emitters. The limiting frequency characteristics of a mechanical phase corrector (in which the mirror is moved by means of piezoelectric drives) are inversely proportional to its mass and hence to its size. The decrease in size necessary to shorten the response time leads to an increase in the optical loading of its optical components.

The placing of phase correctors at the input to optical amplifiers in the region of low power density has its limitations. In order to guarantee the compensation of perturbations, the power-radiation wavefront must be analysed in the same place as the signal wavefront. In order to reduce the background noise, the signal-wave phase must be analysed at the output from power amplifiers. The relationship between the radiation phases in the correction plane and in the analysis plane of the corrected radiation must be single-valued to ensure a high rate of correction.

This condition can be ensured most simply by the heterodyne reception of radiation and by the separation of the amplification channels [9], whereupon one amplification channel corresponds to one measurement point. In this case, the matrix representing the conversion of the phase-sensor signals into the corrector control signals is diagonal. This method employs the piston correction of perturbations in which the local slopes of the wavefront are not compensated. The smallness of the residual perturbations is ensured by the selection of the correction step (i.e. the corrector size). The heterodyne reception ensures a high precision of the phase measurement even under the conditions of a very low signal-wave power [10].

The serious technical problem of organising the distribution of the master-oscillator radiation between the amplification channels arises when the number of such channels is large. At the entry to all the channels, the master oscillator radiation should have identical parameters: power, cross section, and angular spectrum. On the other hand, the operation of phase conjugation presupposes that the master-oscillator radiation is always of single-mode single-frequency nature. This means that we are able to abandon a single master oscillator and to construct the linear adaptive system on the basis of emitters with independent master oscillators. The phase locking of independent emitters by locking to heterodyne radiation has been investigated not only analytically (for example in Ref. [11]) but also experimentally [12].

A key problem in this approach is the equalisation of the emission frequencies of the master-oscillator radiations. An approximate equalisation of the frequencies may be ensured by means of intracavity frequency modulators on the basis of measurements of the frequency and phase of the beats between the laser radiation and the radiation from a reference source, the role of which is assumed by the heterodyne in the given instance. The residual frequency difference may be regarded as a variable phase shift, which varies linearly with time. The phase modulator, the response time of which makes it possible to compensate for this shift so rapidly that the residual error does not then exceed the maximum permissible error of the phase locking, is functionally equivalent to a precision frequency-equalisation circuit.

The characteristic features of the heterodyne phase detection [13, 14] made it possible to organise the operation of the adaptive circuit in such a way that the phase modulator performed two functions simultaneously: it equalised the emitter frequencies and conjugated their phases relative to the phase distribution of the beacon signal. In heterodyne phase detection, the difference between the signal- and heterodyne-radiation phases is measured at the difference frequency. If the difference between the power- and heterodyne-radiation frequencies differs in sign from the difference between the signal- and heterodyne-radiation frequencies, the phase conjugation procedure compensates at the same time for the phase perturbation due to the frequency mismatch. The equalisation of the emitter frequencies for different signs of the difference between the power- and signal-radiation frequencies relative to the heterodyne frequency is demonstrated below.

The proposed procedure combines, as it were, two procedures: the phase locking of independent emitters with frequency equalisation and the phase conjugation of power radiation with signal radiation. A system employing such an approach can therefore be reasonably called a system for the conjugate phase locking of independent emitters. Such an approach has an advantage over the traditional methods of linear adaptive optics: the optical system of the apparatus is free of the difficult to align and inconvenient system for distributing the master-oscillator radiation among the channels. The task of frequency matching the channels is performed by the phase conjugation loop always present in all adaptive systems with a long time of the propagation of radiation from the correction plane to the phase-locking plane and conversely. This advantage is specially perceptible in high-power systems with a large cross section.

4. Organisation of the reference wavefront in a conjugate phase-locking system

For a specified output aperture, the problem of the generation of a reference wavefront, relative to which the phase distributions of the signal and power radiations are measured, is no less topical. For the solution of this problem, we shall consider the heterodyne phase detection procedure in which the phase difference between the analysed and heterodyne radiations is measured. With its aid, we can measure two phase differences in the analysis plane: $\varphi_1 = \varphi_\mathrm{b} - \varphi_\mathrm{h}$ and $\varphi_2 = \varphi_\mathrm{p} - \varphi_\mathrm{h}$, where φ_b, φ_p, and φ_h are the phases of the beacon-signal, power, and heterodyne radiations, respectively. By controlling the power-radiation phase in such a way that the sum of the phase differences is zero, we obtain an expression for the power-radiation phase: $\varphi_\mathrm{p} = -\varphi_\mathrm{b} - 2\varphi_\mathrm{h}$. In this algorithm, the doubled heterodyne phase remains uncompensated in the phase-conjugation procedure.

For a small cross section of the analysed beam, its radiation is as a rule mixed with the plane wavefront of the heterodyne radiation on the planar surface of the optical component, which ensures the equality of the uncompensated term at all points on the latter. In the case considered, the problems due to the large size of the output aperture are aggravated by the problems associated with the thermal deformations of the surface, playing the role of the analysis plane, owing to the high intensity of the radiation incident on it.

Two approaches to the solution of this problem have been proposed. The first consists of the separation of a single analysis surface into a set of planes on each of which the phase distributions are analysed relative to the phase of the local heterodyne radiation. In this approach, it is useful to introduce the concept of a module which contains one heterodyne, one analysis plane, one output beam expander, and an array of laser systems. The local heterodynes of all the modules are frequency- and phase-locked to a single reference heterodyne with the aid of the algorithm described below.

The second approach is used in the intramolecular conjugate phase locking of emitters and involves the measurement of the doubled heterodyne radiation phase in the analysis plane with subsequent allowance for it in the phase-conjugation algorithm. The heterodyne phase is measured in the analysis plane in the following manner. The low-noise heterodyne radiation is filtered and collimated to a relatively small cross section. This radiation serves as a reference and its wavefront is formed with a planar profile to within an error not exceeding the maximum permissible phase-locking error. It passes through the beam expander and is incident on the analysis plane perpendicularly to the latter. After reflection from the analysis plane, the radiation passes through the beam expander in the opposite direction and enters the heterodyne wavefront analyser.

In the analyser, it is mixed with auxiliary radiation having a planar wavefront and a displaced frequency. As a result, we obtain information about the doubled heterodyne-radiation phase in the analysis plane because of the round trip (there and back) of the radiation from the analyser to the analysis plane. In order to simplify the construction of the corresponding distributions, all the sensor arrays are arranged in such a way that the optical axis of the radiation of one laser passes through the centres of the detector planes of the given emitter. In this case, allowance for the doubled heterodyne phase in the analysis plane reduces to the simple addition of the phases measured by the corresponding sensors.

5. Conjugate phase locking in a system with a single telescope

The general principle of the operation of a conjugate phase-locking system can be most easily explained in relation to a system with a single heterodyne and only one analysis plane of the phase distributions. Fig. 2 presents a possible version of the construction of a conjugate phase-locking system. The radiation from laser systems is transformed with the aid of the output telescopes of the emitters and the shared convex auxiliary mirror into a plane wave with a smaller cross section which is incident on a flat plate. A diffraction phase grating is formed on the working surface of the plate with

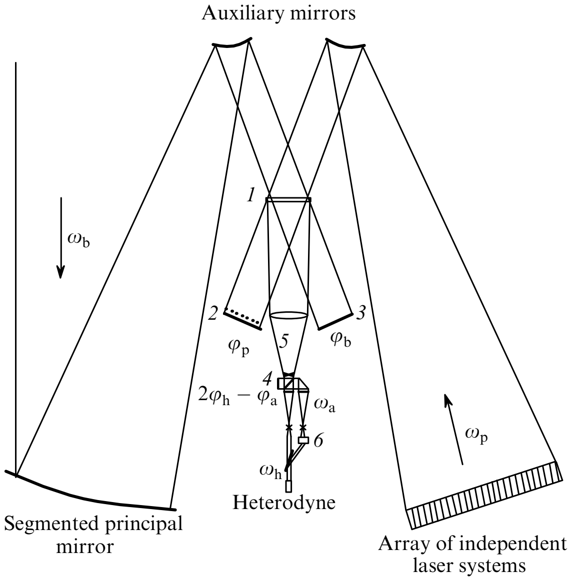

Figure 2. Conjugate phase-locking system for independent laser emitters based on a scheme with a single analysis plane: (1) transparent plate with a phase grating and a highly reflecting interference coating (analysis plane); (2–4) phase distribution sensors for power, beacon-signal, and heterodyne radiations, respectively; (5) heterodyne beam expander; (6) acousto-optical modulator (φ_a, ω_a — radiation phase and frequency).

a highly reflecting interference coating deposited on top of it. This surface plays the role of the plane in which the spatial distributions of both the power-radiation and the beacon-signal-radiation phases are analysed. For this purpose, the heterodyne-laser radiation is incident on this surface from the side of the plate.

The angles of incidence of the beams and the period of the diffraction phase grating were chosen in such a way that the axis of the heterodyne-laser radiation coincided with the beacon-signal radiation axis on reflection in the first order of the grating and with the laser-system radiation axis on reflection in the first negative (minus one) order. On reflection in the zero order the heterodyne radiation is then propagated exactly backwards. The sensor array in the first order of the diffraction grating measures the phase difference between the beacon-signal wave and the reference heterodyne wave. The array in the other first (minus one) order measures the phase of the emitters relative to the heterodyne phase. The attenuation of the radiation intensity in the given channel is attained with the aid of a mask, stops, and filters.

In order to monitor the distribution of the heterodyne phase in the analysis plane, the backreflected heterodyne-radiation is mixed with the auxiliary radiation and is applied to the third sensor array. It measures the phase distribution corresponding to the distribution of the doubled heterodyne phase in the working plane because both mixed fronts are planar at the input to the monitoring system for the reference wavefront. This is ensured by means of angular selectors and optical components with small aberrations. In order to generate the auxiliary-radiation wavefront, part of the heterodyne radiation is applied to an acousto-optical modulator, which effects the necessary frequency shift.

A version of the optical system of the laser array is presented in Fig. 3. The radiation from the master oscillator, containing a frequency modulator and a mode selector, enters the power amplifier through a phase modulator. In order to maintain the beam quality, it is useful to employ a slit power amplifier [15] with a geometrical beam expander (in the case of a solid-state active medium, a slab amplifier [16]). An amplifier of this type makes it possible to ensure in the simplest manner the pumping of the active medium and, what is most important, the effective removal of heat from both types of lasers considered.

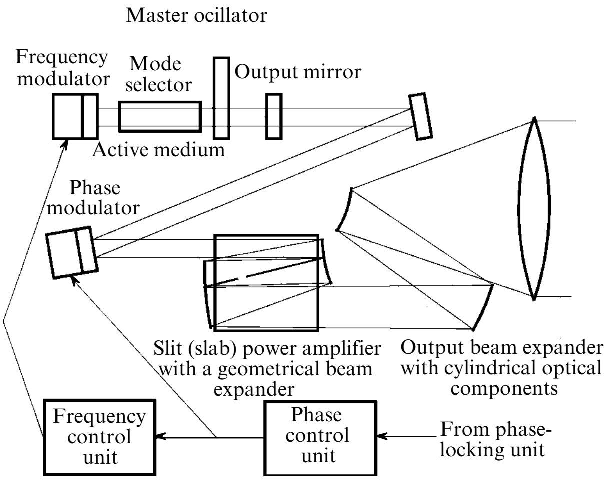

Figure 3. Optical setup for a laser system.

The heterodyne-laser frequency is locked to the beacon-signal-radiation frequency in such a way that the frequency difference falls within the active band of the reception system. The radiation frequency of each laser system is in its turn locked to the heterodyne-laser radiation frequency. The dynamic range of the phase modulator is ensured with the aid of a unit for the control of the master-oscillator frequency (Fig. 3), which alters it in such a way that the signal reaching the phase modulator is returned to the centre of the modulator range.

6. Algorithm for intramolecular frequency – phase matching

In order to discover the principles governing conjugate phase locking, we shall examine the signals observed in the analysis plane of the phase distributions. On the detector array located in the first order of the phase grating of the working plate, the field of the beacon radiation $A_{\mathrm{b}}\cos(\omega_{\mathrm{b}}t+\varphi_{\mathrm{b}})$ is mixed with the field of the heterodyne radiation $A_{\mathrm{b}}\cos(\omega_{\mathrm{b}}t+\varphi_{\mathrm{h}}+\varphi_{\mathrm{g}})$. Here, φ_{g} is a random phase of the grating, which is added to the heterodyne phase φ_{h} on reflection of its radiation in the first order of the grating. The best signal then assumes the following form:

$$A_1 = 2A_{\mathrm{b}}A_{\mathrm{h}}\cos[(\omega_{\mathrm{b}}-\omega_{\mathrm{h}})t+\varphi_{\mathrm{b}}-\varphi_{\mathrm{h}}-\varphi_{\mathrm{g}}] \ . \qquad (1)$$

On reflection in the minus first order, the random-phase shift is the same but its sign is different. The power-laser radiation field $A_{\mathrm{p}}\cos(\omega_{\mathrm{p}}t+\varphi_{\mathrm{p}})$ is then mixed on the second array with the heterodyne-radiation field $A_{\mathrm{h}}\cos(\omega_{\mathrm{h}}t+\varphi_{\mathrm{h}}-\varphi_{\mathrm{g}})$:

$$A_2 = 2A_{\mathrm{p}}A_{\mathrm{h}}\cos[(\omega_{\mathrm{h}}-\omega_{\mathrm{p}})t+\varphi_{\mathrm{h}}-\varphi_{\mathrm{p}}-\varphi_{\mathrm{g}}] \ . \qquad (2)$$

As will be shown below, the phase-conjugation procedure ensures the mutual cancellation of the random-phase shifts on the grating in the diffraction of the heterodyne radiation into phase-grating orders with opposite signs. In order that the phase conjugation procedure ensures simultaneously also the precise equalisation of the laser frequencies, the heterodyne-radiation frequency is located between the beacon-signal and power-emitter frequencies, for example $\omega_{\mathrm{b}}>\omega_{\mathrm{h}}>\omega_{\mathrm{p}}$. This determines the signs of the corresponding phase terms.

The signals defined by formulas (1) and (2) are actually observed at the outputs of the corresponding narrow-band amplifiers. For the phase measurements, the signals obtained are compared with the reference radio-frequency oscillations $A_{\mathrm{rb}}\cos(\omega_{\mathrm{rb}}t+\varphi_{\mathrm{rb}})$ and $A_{\mathrm{rp}}\cos(\omega_{\mathrm{rp}}t+\varphi_{\mathrm{rp}})$ by means of balanced modulators and square-law phase detection. The circuits for the initial frequency locking in the local heterodyne and in the laser system must ensure the following locking conditions: $(\omega_{\mathrm{b}}-\omega_{\mathrm{h}}-\omega_{\mathrm{rb}})\tau_{\mathrm{a}}<\Delta\varphi$ and $(\omega_{\mathrm{h}}-\omega_{\mathrm{p}}-\omega_{\mathrm{rp}})\tau_{\mathrm{a}}<\Delta\varphi$, where $\Delta\varphi$ is the error in the determination of the phase, τ_{a} is the duration of the phase analysis. The difference between the radio frequencies ω_{rb} and ω_{rp} is necessary to isolate the weak beacon against the background of the high-power continuous illumination of the detectors by the radiation from the power lasers.

As can be seen from the description of the optical system, the auxiliary-radiation frequency is rigidly locked to the heterodyne frequency with the aid of an acousto-optical modulator. In order to avoid strays from the high-power radiation of the laser systems, a third beat frequency [the radio signal $A_{\mathrm{rh}}\cos(\omega_{\mathrm{rh}}t+\varphi_{\mathrm{rh}})$] is used for the square-law phase detection. On excitation of an acoustic wave in the modulator with the aid of the same signal, a simple and time-independent expression is obtained for the phase measured by the third array of heterodyne sensors:

$$\varphi_3 = 2\varphi_{\mathrm{h}} + \varphi_{\mathrm{c}} \,, \tag{3}$$

where φ_{c} is a constant which is unique for all the detectors of the array.

In contrast to formula (3), the expressions for the phase differences measured by the first and second arrays contain the time-dependent terms

$$\begin{aligned} \varphi_1 &= (\omega_{\mathrm{b}} - \omega_{\mathrm{h}} - \omega_{\mathrm{rb}})t + \varphi_{\mathrm{b}} - \varphi_{\mathrm{h}} - \varphi_{\mathrm{rb}} - \varphi_{\mathrm{g}} \,, \\ \varphi_2 &= (\omega_{\mathrm{h}} - \omega_{\mathrm{p}} - \omega_{\mathrm{rp}})t + \varphi_{\mathrm{h}} - \varphi_{\mathrm{p}} - \varphi_{\mathrm{rp}} - \varphi_{\mathrm{g}} \,. \end{aligned} \tag{4}$$

The phase of the radiation from the corresponding laser emitter φ_{p} is altered with the aid of the phase modulator in such a way that the following equality holds:

$$\varphi_2 = \varphi_1 + \varphi_3 \,. \tag{5}$$

From expressions (3)–(5), we obtain an expression for the phase of the controlled laser system:

$$\varphi_{\mathrm{p}} = (2\omega_{\mathrm{h}} - \omega_{\mathrm{b}} - \omega_{\mathrm{p}} + \omega_{\mathrm{rb}} - \omega_{\mathrm{rp}})t - \varphi_{\mathrm{b}} - \varphi_{\mathrm{c}} + \varphi_{\mathrm{rb}} - \varphi_{\mathrm{rp}} . \tag{6}$$

We substitute the phase obtained in the expression for the laser-radiation field

$$E_{\mathrm{p}} = A_{\mathrm{p}} \cos[(2\omega_{\mathrm{h}} - \omega_{\mathrm{b}} + \omega_{\mathrm{rb}} - \omega_{\mathrm{rp}})t - \varphi_{\mathrm{b}} - \varphi_{\mathrm{c}} + \varphi_{\mathrm{rb}} - \varphi_{\mathrm{rp}}] . \tag{7}$$

It is seen from formula (7) that all the laser systems emit at the same frequency $2\omega_{\mathrm{h}} - \omega_{\mathrm{b}} + \omega_{\mathrm{rb}} - \omega_{\mathrm{rp}}$ and the phase distribution of the high-power radiation in the analysis plane differs from the phase distribution of the beacon-signal radiation solely by the sign. The constant phase shift $\varphi_{\mathrm{rb}} - \varphi_{\mathrm{rp}} - \varphi_{\mathrm{c}}$, which is the same for all the emitters, does not play any role.

Expression (6) makes it possible to formulate the condition for the efficient operation of the phase modulators:

$$(2\omega_{\mathrm{h}} - \omega_{\mathrm{b}} - \omega_{\mathrm{p}} + \omega_{\mathrm{rb}} - \omega_{\mathrm{rp}})\tau_{\mathrm{c}} < \Delta\varphi \,,$$

where τ_{c} is the phase-correction time. This condition imposes the requirements of precision in locking the frequency of the heterodyne radiation to the frequency of the laser beacon and also in locking the emission frequency of the laser system to the heterodyne frequency. It also determines the sensitivity of the frequency modulators of the emitters.

All the phases of the signals are determined in the working analysis plane. Despite the fact that the detector arrays are at a certain distance from the analysis plane, the difference between the phase shifts for close frequencies may be neglected if $\Delta\nu l/c < \Delta\varphi$, where $\Delta\varphi$ is the error in the determination of the phase; c is the velocity of light; $\Delta\nu$ is the frequency difference; l is the distance at which the phase shift is determined. For a distance of 10 m and an error of phase determination of $\pi/10$, the frequency difference should not exceed 10 MHz.

7. Disadvantages of a system with a single output mirror and the modular concept

The size of the principal mirror of the output beam expander in the system under consideration is so large that the mirror must be sectioned. However, even in this case the rotation of the output telescope together with all the auxiliary components and the casing, ensuring the rigidity of the telescope and also the rigidity of its linkage to a retroreflector, constitutes a serious technical problem even if one disregards the energy expenditure. Furthermore, the output beam expander of the lunar module cannot be in principle shielded from the solar thermal effect, the intensity of which under the conditions of the perpendicular incidence of radiation reaches 1.3 kW m^{-2} [17]. The thermal distortions generated have the amplitude (or the magnitude of deflection) proportional to the mirror diameter. Hence, there is a high probability that they will extend beyond the limits of the working range of the methods of adaptive optics under consideration.

This problem may be solved by abandoning a single output beam expanders and by resorting to a modular design, each module of which has its own independently rotatable telescope (Fig. 4). Such a solution of the problem is possible by virtue of the relatively small field of vision of the system because the beam expanders in the module should be separated by distances of the order of 1% of their size in order to avoid their mutual vignetting. This reduces the radiation delivery efficiency by no more than 2%.

The main feature of such a system from the standpoint of the phase-locking procedure is that, together with a single heterodyne, it employes an array of heterodynes frequency- and phase-locked to a shared reference heterodyne. On the one hand, this type of updating appreciably complicates the design, but, on the other, it removes the requirement for the high power of the heterodyne and makes it possible to increase the sensitivity of the phase detectors of the signal wave by increasing the power of the heterodyne on the detector. Moreover, the optical power absorbed in the ensemble of working plates is reduced greatly thereby.

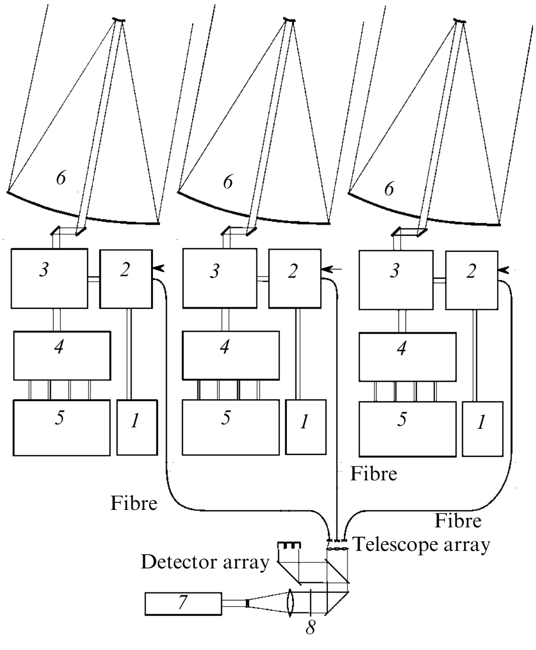

Figure 4. Relative disposition of modules (in relation to three neigh-bouring modules) and the system for the phase locking of local hetero-dynes to the radiation of a reference heterodyne: (1) local-module heterodyne; (2) system for the phase locking of a local-module hetero-dyne; (3) phase-conjugation system; (4) beam-convergence system; (5) array of laser systems; (6) output telescope; (7) reference heterodyne; (8) analysis plane of the reference-heterodyne phase.

The difference between the given algorithm and the method examined above is that the phase difference between the local heterodynes is not measured but eliminated. For this purpose, the radiation of all the module heterodynes travels along the optical single-mode fibres to the system in which a comparison is made with the phase of a reference heterodyne, the frequency of which is somewhat displaced relative to the frequencies of the module heterodynes. The radiation from the reference heterodyne is distributed among the modules through the same fibre system.

The optical system of the module is illustrated in Fig. 5. Each module consists of an output beam expander, the transverse dimensions of which are equal to those of the module, an array of laser systems, and a system for conjugate phase locking to the local heterodyne. Furthermore, the module includes systems for ensuring the convergence of the laser-system rays, for the rough guidance of the module radiation onto an object, for the monitoring of the wavefront of the local-heterodyne radiation, and for the phase locking of the latter to the radiation of the reference heterodyne.

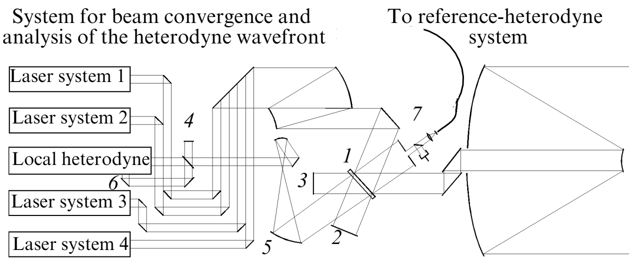

Figure 5. Optical setup of the module: (1) analysis plane of the phase distributions in the form of a transparent plate with a phase grating and a reflecting coating; (2–4) phase distribution sensors for power, beacon-signal, and heterodyne radiations, respectively; (5) heterodyne-beam expander; (6) acousto-optical modulator; (7) system for the phase locking of a local heterodyne.

The system for the convergence of rays forms a single output aperture in the laser-system array and matches it to the input pupil of the output beam expander. The combined radiation wavefront is incident on plate (1) with the phase grating and the reflecting coating, the surface of which plays the role of the working analysis plane. The radiation from the local heterodyne is incident on the same surface from the side of the plate and the radiation from the reference heterodyne of the phase-locking system of the local heterodyne (7) is incident from the side of the reflecting coating. For the algorithm employed to take into account the phase distribution of the heterodyne in the analysis plane, the requirements in respect of the flatness of the plate become much less stringent, which is of particular interest under the conditions of a high radiation intensity.

The mutual disposition of the modules (in relation to three neighbouring modules) and the system for the phase locking of local heterodynes to the radiation of the reference heterodyne are presented in Fig. 4. The phase of the beats between the local-heterodyne radiation and the radiation from the reference heterodyne is measured in the working analysis plane of the module and in the analysis plane of the reference heterodyne. The local heterodyne is located at the centre of the array of emitters instead of the laser system, the field of vision of which corresponds to the central opening in the main mirror of the output beam expander of the module. In order to minimise losses, the size of the central opening should be identical with the transverse dimensions of the laser system.

8. Algorithm for the phase locking of the heterodynes in the modules to the reference heterodyne

The algorithm for the phase locking of the modules is explained in Fig. 6. The intramodular phase locking of the laser systems is performed on the basis of the algorithm described above. It is seen from formula (7) that, even when the frequencies of the local heterodynes are equal, the radiation from the laser systems in the analysis plane contains a random phase φ_c, which is the same for all the emitters of the given module. In order to eliminate its influence, we shall proceed to the measurement of the relative doubled phase of the local heterodyne. For this purpose, we subtract the phase at the centre of the working plate from the phase distribution measured by the third array [see expression (3)]. Hence, we obtain $\varphi_3' = 2\varphi_h - 2\varphi_{h0}$. As a result of such correction of the algorithm, the term φ_c in expression (7) must be replaced by the term $-2\varphi_{h0}$. In this case, the phase locking of the modules requires the equalisation of the frequencies of all the local heterodynes and of their doubled phases in the centre of the analysis plane.

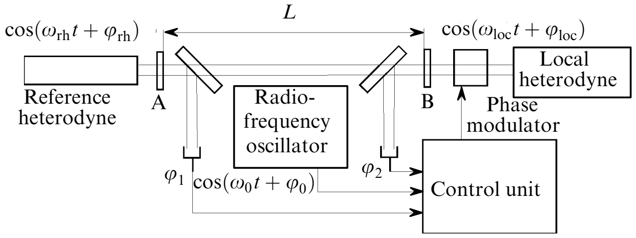

Figure 6. Schematic illustration explaining the algorithm for the phase locking of a local heterodyne to the radiation of a reference heterodyne (A — reference analysis plane, B — working analysis plane).

We postulate that the field of the reference heterodyne in the reference analysis plane A has the form $E_{rh}\cos(\omega_{rh}t + \varphi_{rh})$, while the field of the local heterodyne in the centre of the working analysis plane of the module (plane B), where beats also arise, has the form $E_{rh}\cos(\omega_{loc}t + \varphi_{loc})$. Suppose that $\omega_{rh} > \omega_{loc}$, whereupon the signal of the beats with the phase φ_1 on the first detector (Fig. 6) has the form $E_1 = E_{10}\cos[(\omega_{rh} - \omega_{loc})t + \varphi_{rh} - \varphi_{loc} - k_{loc}L]$, whereas the signal of the beats with the phase φ_2 on the second detector has the form $-E_2 = E_{20}\cos[(\omega_{rh} - \omega_{loc})t + \varphi_{rh} - k_{rh}L - \varphi_{loc}]$, where L is the optical length of the path between planes A and B, while $\boldsymbol{k}_{rh,loc}$ are the corresponding wave vectors. When these signals are compared with the reference signal $E_{rrh}\cos(\omega_{rrh}t + \varphi_{rrh})$, applied to the phase detectors from the oscillator shared by all the modules, the following phases are obtained at the output from the detectors:

$$\begin{aligned} \varphi_1 &= (\omega_{rh} - \omega_{loc} - \omega_{rrh})t + \varphi_{rh} - \varphi_{loc} - \varphi_{rrh} - k_{loc}L\,, \\ \varphi_2 &= (\omega_{rh} - \omega_{loc} - \omega_{rrh})t + \varphi_{rh} - \varphi_{loc} - \varphi_{rrh} - k_{rh}L\,. \end{aligned} \tag{8}$$

With the aid of the phase modulator controlling the phase of the local heterodyne in the working plane, the phase φ_1 was altered in such a way that $\varphi_1 + \varphi_2 = 0$ and the residual error did not exceed the maximum permissible phase-locking error. In this case, $2\varphi_{\rm loc} = 2(\omega_{\rm rh} - \omega_{\rm loc} - \omega_{\rm rrh})t + 2\varphi_{\rm rh} + 2\pi n + (k_{\rm rh} - k_{\rm loc})L$, where n is an integer. If the term $(k_{\rm rh} - k_{\rm loc})L$ also does not exceed the maximum permissible phase-locking error, it can be neglected. For a distance of 20 m and a phase-locking error of $\pi/15$, the frequency difference between the heterodynes should not exceed 500 kHz. In this case, $\varphi_{\rm loc} = (\omega_{\rm rh} - \omega_{\rm loc} - \omega_{\rm rrh})t + \varphi_{\rm rh} + \pi n$ and the local-heterodyne signal in the analysis working plane of the module B can be formulated as follows:

$$E_{\rm loc} = E_{\rm loc0}\cos[(\omega_{\rm rh} - \omega_{\rm rrh})t + \varphi_{\rm rh} - \varphi_{\rm rrh} + \pi n] \ . \tag{9}$$

The expression obtained demonstrates convincingly that the signals from all the local heterodynes in the analysis planes have the same frequency $\omega_{\rm rh} - \omega_{\rm rrh}$ and the same doubled phase $2\varphi_{\rm rh} - 2\varphi_{\rm rrh}$. For the algorithm employed, this assertion is equivalent to the assertion that the modules are phase-locked.

9. Conclusions

Theoretical analysis of the algorithm for linear conjugate phase locking showed that, for certain ratios of the signal-, heterodyne-, and power-radiation frequencies, the algorithm can be used for the precise equalisation of the frequencies of the independent emitters. The necessary precision of the preliminary (rough) equalisation of frequencies is determined by the frequency – temporal parameters of the apparatus used for phase analysis and correction. The use of the algorithm for linear frequency- and phase-locking of the heterodyne radiation to the radiation of a reference source makes it possible to proceed from a single analysis plane to a set of phase-locked planes and to the modular principle of the construction of an emitter.

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References

1. Eguchki K, Niino M, Arashi H, et al. Second Wireless Power Transmission Conference (WPT95), Kobe, Japan, 1995
2. Mak A A, Sherstobitov V E, Kuprenyuk V I, et al. Optich. Zh. **65** (12) 52 (1998) [J. Opt. Technol. **65** 992 (1998)]
3. Vasil'ev M V, Venediktov V Yu, Leshchev A A, et al. Izv. Akad. Nauk SSSR Ser. Fiz. **55** 260 (1991)
4. Kornev A F, Pokrovskiĭ V P, Soms L N, et al. Optich. Zh. (1) 10 (1994) J. Opt. Technol. **61** 10 (1994)
5. Zel'dovich B Ya, Pilipetsky N F, Shkunov V V Principles of Phase Conjugation (Berlin: Springer, 1985)
6. CIS Selected Papers: High-power multibeam lasers and their phase locking Proc. SPIE Int. Soc. Opt. Eng. **2109** (1003)
7. Vorontsov M A, Shmal'gauzen V I Printsipy Adaptivnoĭ Optiki (Principles of Adaptive Optics) (Moscow: Nauka, 1985)
8. 'Adaptive optics' (Topical issue) (Ed. D L Fried) J. Am. Opt. Soc. **67** (3) (1977)
9. Hayes C L, Brandewie R A, Davis W C, Mevers G E J. Opt. Soc. Am. **67** 269 (1977)
10. Gryaznov N A Optich. Zh. **65** (4) 32 (1998) [J. Opt. Technol. **65** 284 (1998)]
11. Wang C P Appl. Opt. **17** 83 (1978)
12. Hayes C L, Laughman L M Appl. Opt. **16** 263 (1977)
13. Protopopov V V, Ustinov N D Lazernoe Geterodinirovanie (Laser Heterodyne Radiation) (Moscow: Nauka, 1985)
14. Belousova I M, Gryaznov N A, Zyuzin O M, et al. Kvantovaya Elektron. (Moscow) **16** 1617 (1989) [Sov. J. Quantum Electron. **19** 1041 (1989)]
15. Dutov A I, Novoselov N A, Kuleshov A A Proc. SPIE Int. Soc. Opt. Eng. **2788** 103 (1996)
16. Kiriyama H, Nishida K, Yamanaka M, et al. Proc. SPIE Int. Soc. Opt. Eng. **3264** 30 (1998)
17. Makarov E A, Kharitonov A V Raspredelenie Energii v Spektre Solntsa i Solnechnaya Postoyannaya (Energy Distribution in the Solar Spectrum and the Solar Constant) (Moscow: Nauka, 1972)