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Phasing of several gain channels for coherent and spectral combining of laser beams

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Abstract. **A system for maintaining a constant phase difference between several laser channels is designed and an algorithm of its operation under a slow (with a characteristic time of no less than 100 ms) variation in the radiation phase in a channel is developed. Different possible regimes of operation of the measurement system and versions for phase difference maintaining are analysed and an optimal algorithm is elaborated. Long-term stable operation of the system under thermal and mechanical effects on the active medium is experimentally demonstrated by the example of a seven-channel fibre amplifier with a working wavelength of 1.064 μm.**

Keywords: *phase modulation, lock-in detection, coherent and spectral combining.*

1. Introduction

Coherent and spectral combining of laser beams, which has been actively developed in the last years, led to a significant increase in the power of both fibre and solid-state laser systems [1–4]. In this case, the cw lasing power reaches several tens of kilowatts with conservation of high quality of the resulting radiation, close to the diffraction limit [5, 6]. Both methods have advantages and drawbacks. Spectral combining is convenient when using diode or low-power fibre lasers with a relatively low lasing power of a single emitter (to several tens of watts) and a wide emission spectrum [7]. When combining high-power laser beams, the coherent-combining scheme is preferred [8, 9]. On the one hand, coherent combining of laser beams requires monitoring and maintaining the radiation phase in each channel at a specified level with a high accuracy (up to 0.01 rad). On the other hand, it allows one to obtain a high output power (up to 100 kW) without concentrating the entire power on a particular optical element, as in the case of spectral combining.

In this paper we describe an approach to the formation of a system for monitoring and maintaining the radiation phase in several laser channels with an error of no larger than 0.01 rad. Ytterbium-doped fibre amplifiers are used in multichannel multistage fibre and solid-state laser systems with coherent combining in the initial cascades. Therefore, one of the purposes of our study was to form a complex of an all-fibre phase-adjustment system. Since the radiation phase in individual channels changes due to thermal processes (i.e., relatively slowly, for times of several tens of milliseconds), the system for processing the phase-shift data and the system for controlling the radiation phase in the amplifier should provide an operating speed at a level of no worse than 10 ms.

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2. Experimental setup

The laser system, designed according to the oscillator–amplifier scheme, operates as follows (Fig. 1). Initial single-frequency radiation is formed by a master oscillator based on a single-frequency semiconductor laser with a lasing wavelength of 1.064 μm and a spectrum width of ~3 MHz. Then this radiation is separated into eight channels (one reference channel and seven 'power' channels). The latter channels contain a system of amplifiers to raise the radiation power to the desired level. The radiation transmitted through the gain channels is collected into a system of parallel, closely spaced laser beams, which form a synthesised aperture of the laser system. In our case the amplification provided a power level in each channel of no more than 100 mW, because our main goal was not to obtain a maximum output power of the laser system but to measure and maintain in-phase radiation in the channels.

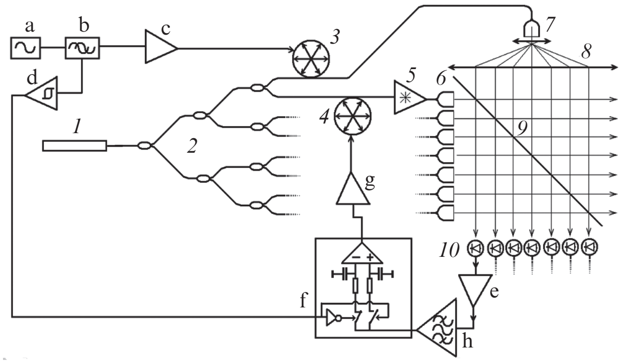


Figure 1. Schematic of the experimental setup.
Optical elements: (*1*) master single-frequency diode laser, (*2*) fibre couplers, (*3*) piezoceramic phase modulator, (*4*) piezoceramic control elements, (*5*) fibre optical amplifiers, (*6*) working-channel collimators, (*7*) reference-channel collimator, (*8*) telescope, (*9*) splitter, and (*10*) photodetectors. Electronic components: (a) harmonic (sinusoidal) oscillator, (b) phase shifter for modulation and reference signals, (c) modulation-signal amplifier, (d) rectangular reference signal generator, (e) photodetector preamplifier, (f) selective preamplifier, (g) lock-in amplifier, and (h) output high-voltage amplifier.

To combine coherently the amplified radiations from the working channels, it is necessary to know the phase in each of them and be capable of controlling it. The reference channel served as a base to phase the working channels. An attempt to fix the interference signal of output radiation at a constant level did not provide desired accuracy and stability. Therefore, one must use modulation techniques, both amplitude and phase (or frequency). Any modulator can be applied: mechanical, electromechanical (piezoceramic or electrodynamic), electro-optical, acousto-optic, etc.

In this study we used a fibre piezoceramic modulator, which consists of a single-mode optical fibre, wound on a cylindrical piezoceramic coil and glued to it. Phase modulation was performed by changing the mechanical stress and optical-fibre length through variation in the geometry of piezoceramic cylinder as a result of applying a periodic control voltage to it. The advantages of this design are simplicity, reliability, and possibility of changing the range of phase modulation by varying the length of the fibre wound on the piezoelectric ceramic, with the characteristics of the control electric signal retained the same. The drawbacks of this configuration are as follows: low modulation frequency (no more than several tens of kHz), hysteresis of piezoelectric ceramic characteristics, and their strong temperature dependence. The latter two can be compensated for by designing a control oscillator with the piezoceramic coil incorporated into the frequency-determining chain. In this case, the amplitude of the control-voltage effect on the coil will be independent of the change in the piezoelectric ceramic characteristic frequency. The reference-signal phase modulation frequency f_m was 11 – 12 kHz in our experiments.

The device for determining and controlling the radiation phase served to specify a current value of the power-channel radiation phase and change it so as to make the phase difference for the radiation in each power channel and the reference channel, measured at the output of the laser system, close to zero. Thus, the working channels will be in-phase, i.e., the radiations through these channels will be coherently combined. The phase-control level was on the order of 3 – 5 wavelengths.

To exclude the influence of active-fibre inhomogeneities on the polarisation of amplified radiation, we applied fibre polarisation controllers. The output power in each power channel was equalised using an attenuator.

The difference signal, which is proportional to the phase difference between the reference and power channels, was selected by combining the radiation of the reference channel and a part of radiation of power channels at heterodyne detectors, individual for each channel. The thus obtained signal was processed in a phase-modulator (PM) control unit and used in the feedback loop to control the PM.

3. Analysis of the operation of the device for determining and controlling the radiation phase

The control system was based on a phase-lock detector, operating in the range near the maximum or minimum of the interference signal. The region of rise or falloff of interference signal intensity is characterised by a maximum peak-to-peak modulation amplitude at the frequency f_m but a weak sensitivity to the phase difference between the reference and power channels.

When working in the range of interference-signal maximum or minimum, where the average phase of the reference signal is shifted by an integer of half-waves with respect to the phases of working channels, there will be modulation of the interference signal at the frequency $2f_m$ for reference-signal-phase modulation amplitudes that do not exceed $\pm\lambda/3$.

The double modulation frequency is due to the identical increase (in the range of minimum) or decrease (in the range of maximum) in the interference signal for both positive and negative half-waves of the modulating signal; therefore, two identical symmetric peaks in the interference pattern will correspond to one period of the reference signal. The lock-in amplifier at the output will provide zero signal, because identical signals arrive at the '+' and '–' inputs of the differential amplifier. Possible operation regimes of the system are presented in Fig. 2.

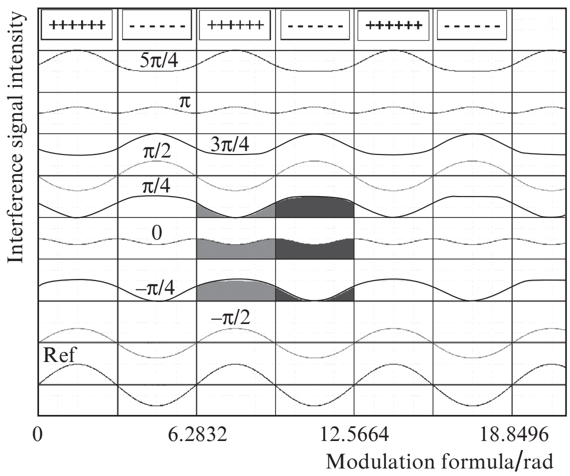


Figure 2. Dependences of the interference signal intensity on the modulation signal phase (curve Ref) and on the shift of working-channel phases with respect to the average phase of the reference channel (curves from π/2 to 5π/4). The lock-in amplifier operation is illustrated in the top: the modulation phase ranges included in the desired signal with '+' and '–' signs are shown.

At the same time, if the phase detunings of the reference and working channels are not equal to an integer of half-waves, the pattern ceases to be symmetric, and the signal at the synchronous-detector output becomes nonzero. Having applied this signal to the control element, which changes the optical path length in the working channel, one can obtain a stable stabilising negative feedback. The polarity of control element switching will depend on the capture point of the interference signal: either in maximum or in minimum.

The lock-in amplifier operates as follows. The interference signal at the output of the photodetector with a preamplifier, in dependence of the modulation phase of the reference signal x, can be written as

$$P = A\cos[B\sin(x + \varphi) + C] + D, \quad (1)$$

where A is the interference amplitude, B is the phase modulation amplitude for the reference channel, φ is the phase shift for mechanical modulation and synchronous signal, C is the phase shift for the average phase of the reference and working channels, and D is a constant component.

The sign and value of A may change, depending on the laser signal value, the gains of the electronic components, and the polarity of piezoelectric ceramic switching. The constant component is cut off by an electronic filter at the input.

The control signal at the output of the key lock-in amplifier can be presented as the difference in the integrated photodetector signals for the first and second modulation half-periods:

$$S = \int_0^{\pi}\cos[B\sin(x+\varphi)+C]\mathrm{d}x = \int_0^{2\pi}\cos[B\sin(x+\varphi)+C]\mathrm{d}x$$

$$= -2\sin C\int_0^{\pi}\sin[B\sin(x+\varphi)]\mathrm{d}x. \quad (2)$$

It can be seen that, when the phase shift C is zero, the control signal is also zero, and the system is in stable equilibrium. At the same time, if C is nonzero, a restoring negative feedback signal arises.

The sensitivity of the system to a change in C is determined by integral (2). At $\varphi = \pi/2$ the quantity $\sin(x+\varphi)$ will alternate symmetrically and integral (2) will turn to zero. Thus, the system will stop responding to variation in C, which is highly undesirable. At $\varphi = \pi$, i.e., at a shift by half-period, when the reference and working channels are not in phase but in antiphase, the sign of integral (2) changes to opposite, the system passes to unstable equilibrium, and even a very small perturbation may immediately switch it to the stable state.

The dependence of the sensitivity of the system on the phase modulation amplitude (depth) is rather interesting (see Fig. 3). First the sensitivity increases with an increase in the amplitude to $\lambda/4$ and even larger (to 2 rad, i.e., to $\lambda/3$) but then decreases and even changes the sign, because at modulation amplitudes above $\lambda/2$ the antiphase components of the interference signal begin to be added.

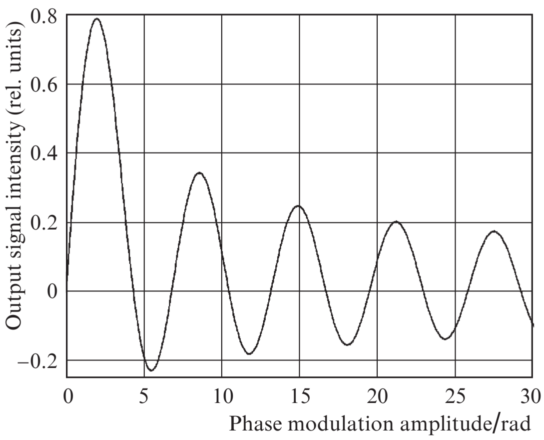


Figure 3. Dependence of the control-system sensitivity on the phase modulation amplitude.

The analysis of operation of the control system based on a key lock-in amplifier provides the following (experimentally verified) recommendations.

(1) It is necessary to prevent the phase difference for the mechanical vibrations of piezoelectric ceramic and the synchronous signal oscillations from exceeding $\pi/4$ in order to exclude sensitivity loss.

(2) One should maintain the modulation amplitude for the optical path length in the reference channel at a level of about $\lambda/3$, because the sensitivity deteriorates at smaller amplitudes, whereas an increase in the amplitude above this level leads to a decrease in sensitivity and may even cause a 'jump' of the system to the antiphase regime.

4. Experimental results

When carrying out experiments, most attention was paid to maintaining the phase difference between the radiations from individual channels at a constant level. A collimator was welded to the output end face of each power channel to form a laser beam about 2 mm in diameter with a divergence of ~1 mrad. In turn, the collimators were glued into a holder in such a way as to make their beam axes intersect at the same point at a distance of 4 m from the holder. The arrangement of the power channel outputs had a hexagonal symmetry (Fig. 4). The interference pattern formed in the screen in the region of laser-beam intersection was observed with a CCD matrix, and its time stability was additionally controlled using a photodiode.

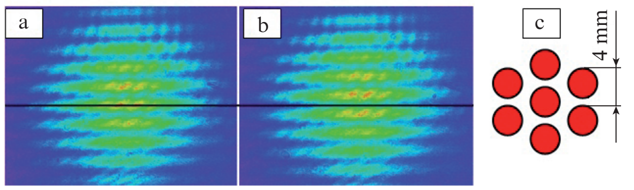


Figure 4. Interference pattern obtained by combining radiations from two channels at (a) $\Delta\varphi = 0$ and (b) $\Delta\varphi = \pi$; (c) arrangement of the output collimators in power channels.

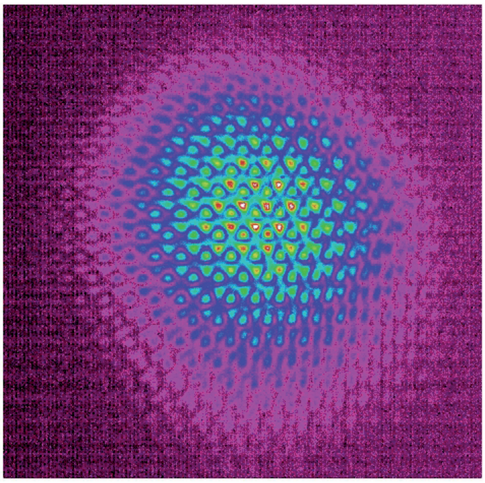
We studied successively the combining of radiations transmitted through laser channels in different versions (by switching off the pump radiation for individual fibre amplifiers). Simultaneous excitation of two channels provided a stable interference pattern (Fig. 4). A constant phase difference Δx between channels was introduced by applying an additional dc voltage to the phase modulator in one of the channels. The interference pattern in Fig. 4a corresponds to $\Delta\varphi = 0$, whereas Fig. 4b illustrates the case $\Delta\varphi = \pi$. It can be seen well that the pattern is shifted by half period.

The operating speed of the feedback loop in the device for maintaining the phase difference was also verified by converging radiations from two channels. It was found that the operating speed of the system is better than 100 ms at a short-term effect on one of the channels (heating for 1 s or an impact with duration of about 20 ms).

Combining of radiations from all seven channels (Fig. 5) also leads to a long-term stable interference pattern (the experiment lasted more than 1 h). The pattern stability was not violated under a slow thermal effect on different channels (with a heating rate of about 10 K min^{-1}). The influence of the operation of the phase-maintenance system on the total radiation intensity of seven channels is shown in Fig. 6.

5. Conclusions

A simple and efficient system for maintaining the phase difference between several laser channels at a constant level was elaborated and its operation algorithm was developed. Stable operation of the entire system was demonstrated by the exam-



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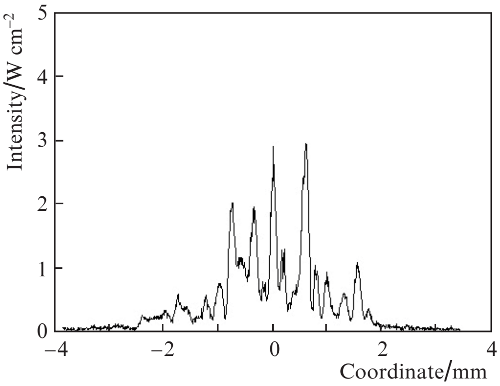

b

Figure 5. (a) Interference pattern and (b) intensity distribution in its transverse cross section, obtained by combining radiations from seven channels.

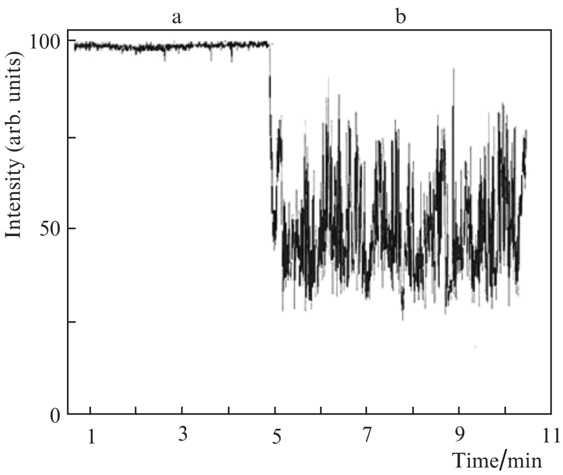

Figure 6. Stability of the total radiation from seven channels in the case of (a) a switched-on and (b) switched-off phase maintenance system.

ple of coherent combining of radiations from seven channels of ytterbium-doped fibre amplifiers. It was shown that this system can be used in higher power laser systems to compensate for the phase difference in laser channels under thermal and mechanical effects on the active medium, which lead to a relatively slow (with a characteristic time longer than 100 ms) variation in the radiation phase in individual channels.

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