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Phasing of two amplifier channels for the coherent combining of laser beams with a total power of 60 W

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Abstract. **We have demonstrated stable operation of a system for maintaining a constant phase difference between two laser channels with a total output power of 60 W. The system is based on a two-channel fibre amplifier with phase modulators based on piezoceramic spools. At a main piezo element modulation frequency of 11 kHz, the phasing time after thermal and mechanical influences on the active medium is 100 ms.**

Keywords: *phase modulation, synchronous detection, coherent combining.*

1. Introduction

The use of coherent and spectral laser beam combining – methods that have been actively developed in recent years – has ensured a considerable growth in the total power of both solid-state and fibre laser systems [1–4]. In particular, cw laser power can reach several tens of kilowatts, without beam quality degradation ($M^2 < 3$) [5,6]. Both beam combining methods have not only advantages but also drawbacks. Spectral combining is rather convenient in the case of lasers with a relatively low power of a single emitter (below a few tens of watts) and a broad emission spectrum [7–9]. In the case of high-power laser beams, coherent combining is more attractive [10–13]. Even though coherent laser beam combining requires that the phase of the light in each channel be monitored and maintained with high accuracy, it allows high output powers (up to 100 kW) to be obtained [14] without concentrating all the power in one optical element, unlike in the case of spectral combining.

This paper describes a system for simultaneously monitoring and maintaining the phase of light in several laser channels using synchronous detection, where each channel has a separate detector. The phasing rate in such a case is independent of the number of channels and is determined mainly by the speed of the phase modulators. Multichannel, multistage solid-state and fibre laser systems with coherent combining in the initial stages use ytterbium-doped fibre amplifiers, so one of our purposes in this work was to make a combined all-fibre phase control system.

This study differs from a previously reported one [15], which addressed the combining of the outputs from two or more channels of a fibre laser system, in the level of the power of light. In Ref. [15], we performed beam combining at powers of 5 W per channel, whereas here the power per channel is 30 W.

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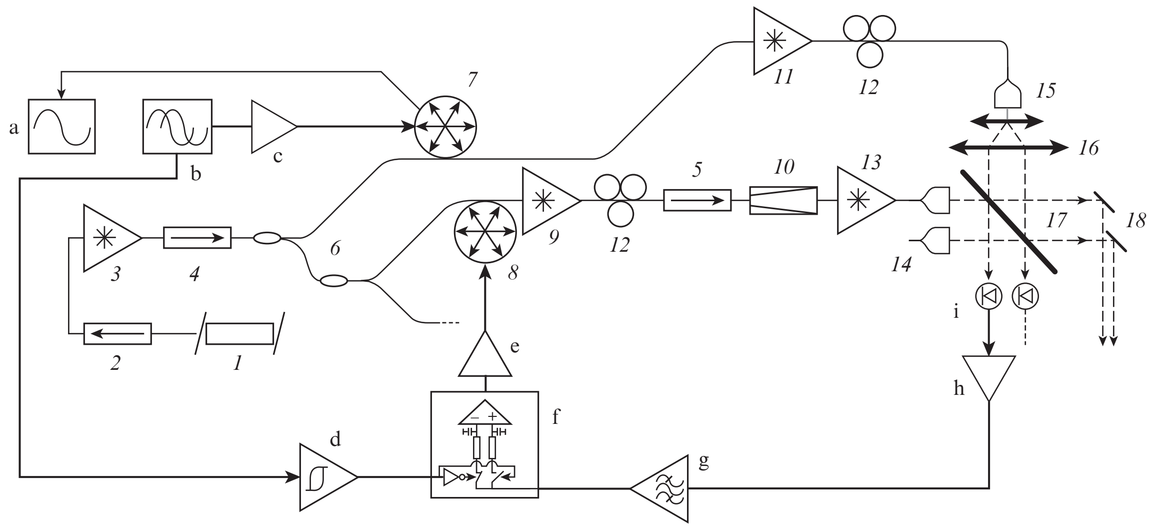
2. Experimental setup

Figure 1 shows a schematic of the experimental setup. The input beam was formed by a master oscillator (*1*) based on a single-frequency semiconductor laser diode [16] with a wavelength of 1080 nm and spectral linewidth of 2.8 MHz. The light was then divided into three channels (one reference channel and two power channels). In the power channels, the light passed through a system of amplifiers and reached the required power level: about 30 W per channel. Next, the amplified light was collected into a system of closely spaced parallel laser beams, thus forming a synthesised aperture of the laser system.

The reference channel was intended for the phasing of the power channels relative to it. Since the phase difference between the power and reference channels has a random character, an attempt to fix the interference signal of the output light at a constant level does not ensure necessary accuracy and stability. Because of this, modulation techniques should be used to produce a phase difference $\Delta\varphi$ according to a certain law in order to know the exact difference between the phase of the reference channel (φ) and that of the power channel (φ_n). If this difference is the same for all the power channels, they will have identical phases.

As phase modulators, we used piezoceramic spools (*7*, *8*) with single-mode fibre wound on them. To modulate the phase of the reference channel and adjust the phases of the power channels, the optical path length in the fibre was varied by stretching the fibre as a consequence of a change in the diameter of the piezoceramic spool. This configuration has the advantages of simplicity and reliability, with the possibility of varying the phase modulation range by changing the length of the fibre wound onto the piezoceramic, without changes in the characteristics of the control signal. Its drawbacks are low modulation frequency (under a few tens of kilohertz), hysteresis and the strong temperature dependence of the physical characteristics of the piezoceramic. The last two drawbacks can be compensated for by making a control generator, whose circuit, determining the oscillation frequency,



Schematic of the experimental setup. Optical components:
(*1*) master oscillator; (*2*) 300-mW two-stage fibre isolator; (*3*, *9*, *11*) GTWave fibre amplifiers; (*4*) 3-W fibre isolator; (*5*) 10-W fibre isolator; (*6*) system of fibre couplers; (*7*) piezoceramic phase modulator; (*8*) piezoceramic control element; (*10*) mode adapter; (*12*) polarisation controllers; (*13*) LMA fibre amplifier; (*14*) collimators of the power channels; (*15*) collimator of the reference channel; (*16*) telescope; (*17*) beam-splitting plate; (*18*) folding mirrors. Electronic components: (a) sine-wave generator; (b) phase shifter of the modulating and reference signals; (c) amplifier of the modulating signal; (d) square reference signal shaper; (e) high-voltage output amplifier; (f) synchronous detector; (g) selective strip preamplifier; (h) preamplifier for the photodetector; (i) fibre-pigtailed photodetectors.

includes the piezoceramic spool. The effectiveness of the influence of the control voltage on the spool will then be independent of the characteristic frequency of the piezoceramic. In our experiments, the reference signal phase modulation frequency was 11 kHz. In this study, the system maintained a near-zero phase difference between the reference and power channels. The stress induced in the fibre by the piezoelectric modulator was shown to cause weak changes in the polarisation of the output beam (less than 1/500 of the general level). To reduce the effect of the piezoelectric modulator on the polarisation, the main modulation frequency was slightly displaced from the resonance frequency.

To exclude the effect of active fibre inhomogeneities on the polarisation of the amplified light, we used optical fibre polarisation controllers (*12*). To improve the interference signal contrast, the output power of the reference channel was amplified to 1.5 W by a fibre amplifier (*11*). To the output end of each power channel we fusion-spliced collimators (*14*), which allowed us to obtain laser beams about 2 mm in diameter with a divergence under 1 mrad. A difference signal proportional to the phase difference between the reference and power channels was separated out upon the combining of the light from the reference channel and some of the light from the power channels in heterodyne detectors individual for each channel. The signal thus obtained was used in the feedback loop for controlling the phase modulators.

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

The control system was based on a synchronous phase detector operating in the region of the maximum or minimum interference signal. In the region of the maximum or minimum interference signal, where the average phase of the reference signal differs from the phases of the power channels by an integer number of half-waves, at reference signal phase modulation amplitudes no higher than $\pm\pi/3$ the interference signal will be modulated at the doubled frequency. In such a case, the output signal of the synchronous detector will be zero, because identical signals enter the positive and negative inputs of the differential amplifier. Possible operation modes are illustrated in Fig. 2. If the phase detunings of the reference and power channels differ from integer numbers of half-waves, the picture becomes asymmetric and the output signal of the synchronous detector is nonzero. Directing the signal to the control element, which varies the optical path length in the power channel, a stable, stabilising negative feedback can be obtained.

The operation of the synchronous detector can be described as follows: At the output of the photodetector with the preamplifier, the interference signal as a function of the reference signal modulation phase φ has the form

$$P = A\cos[B\sin(\varphi + \varphi_{\mathrm{m}}) + C] + D, \tag{1}$$

where A is the interference amplitude; B is the phase modulation amplitude in the reference channel; φ_{m} is the phase difference between the mechanical modulation and sync signal; C is the difference between the average phases of the reference and power channels; and D is a constant component (cut off by an electronic filter).

The control signal at the switching synchronous detector output can be represented as the difference between integrals of the signal from the photodetector over the first and second modulation half-periods:

$$S = \int_0^{\pi}\cos[B\sin(\varphi + \varphi_{\mathrm{m}}) + C]\mathrm{d}\varphi - \int_{\pi}^{2\pi}\cos[B\sin(\varphi + \varphi_{\mathrm{m}}) + C]\mathrm{d}\varphi = -2\sin(C)\int_0^{\pi}\sin[B\sin(\varphi + \varphi_{\mathrm{m}})]\mathrm{d}\varphi. \tag{2}$$

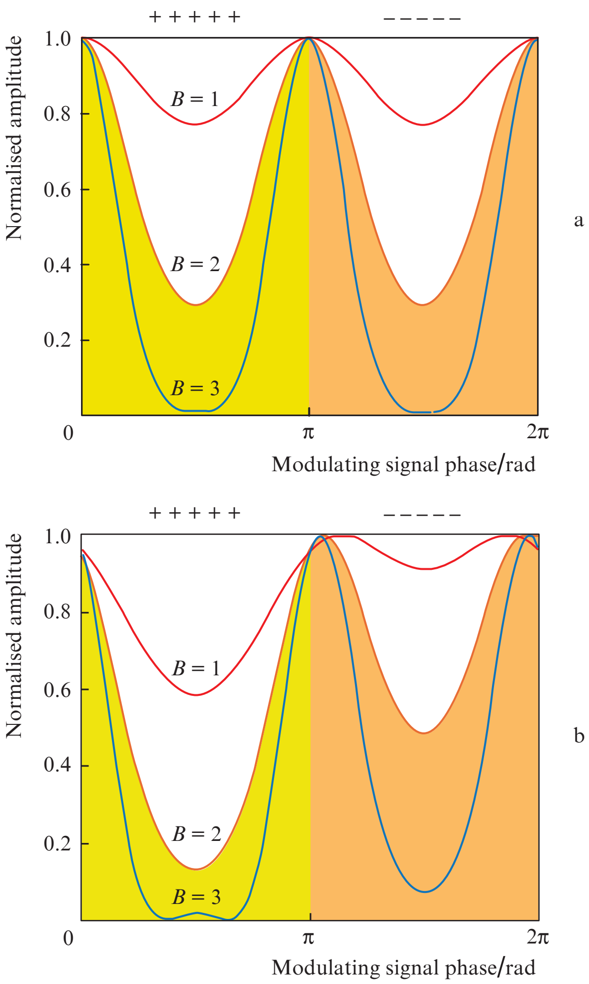


Figure 1. Interference signal amplitude as a function of the modulating signal phase at different modulation amplitudes B and (a) $C = n\lambda/2$ or (b) $C \neq n\lambda/2$. The plus and minus signs over the graphs indicate which phase modulation regions lead to an increase in the wanted signal (+) and which, to a decrease (–).

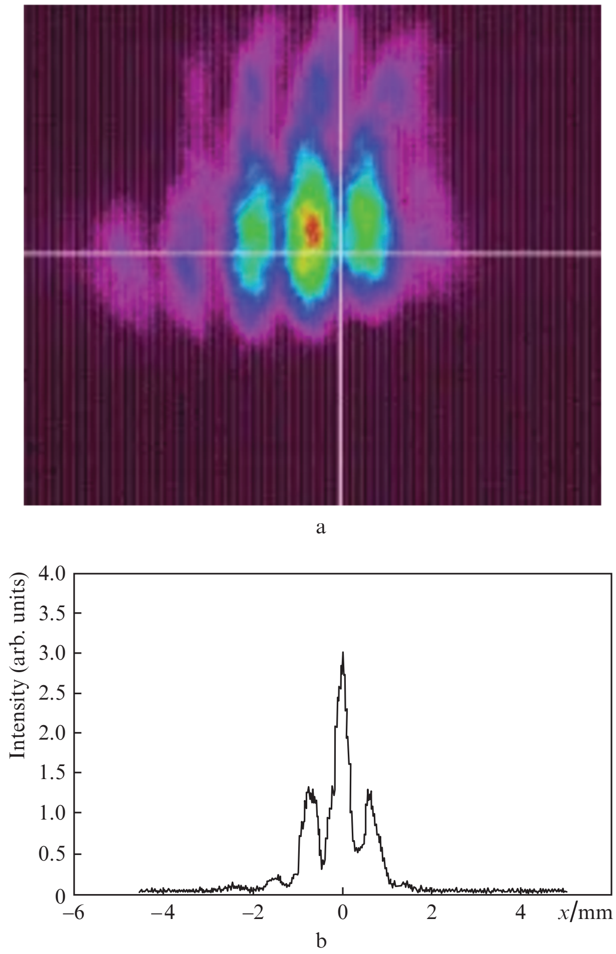


Figure 2. (a) Far-field interference pattern and (b) interference signal intensity profile.

It is seen that, at zero phase difference C, the control signal is zero and the system is in stable equilibrium. If C differs from zero, a restoring negative feedback signal emerges.

The sensitivity of the system to changes in C is determined by integral (2). At $\varphi_m = \pi/2$, $\sin(\varphi + \varphi_m)$ will be symmetrically alternating and integral (2) will become zero. The system will then not respond to changes in C, which is extremely undesirable. At $\varphi_m = \pi$, i.e. upon a half-period shift, where the reference and power channels are not in phase but in antiphase, integral (2) will change sign, the system will be in unstable equilibrium, and the slightest disturbance will drive it into a stable state.

4. Experimental results

The speed of the feedback system in the phase difference control device was checked by combining light from two channels with a total power of 60 W. The interference pattern emerging on a display in the laser beam overlap region was observed using a CCD array (Fig. 3). To obtain one central maximum in the far field, it was necessary to bring together the laser beams to a distance less than $4w$, where w is the laser beam waist radius. The size of the collimators (11 mm diameter) was unsuitable for doing it directly, so a system of reflecting mirrors was used. Since some part of the beam was incident on the edge of a mirror, this distorted the intensity profile. In the case of a short-term external influence (heating for 1 s or a mechanical impact about 20 ms in duration), the response time of the system was estimated at 100 ms (Fig. 4). Oscil-

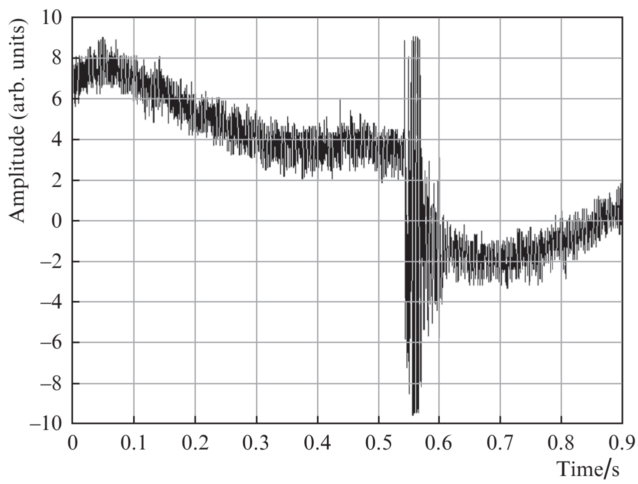


Figure 3. Signal from the synchronous detector.

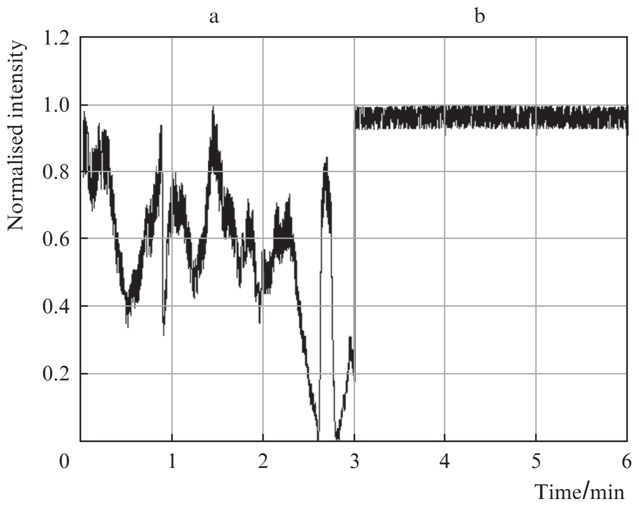


Figure 4. Output intensity in the (a) free and (b) phase locking regimes.

loscope traces of the central maximum in the far-field interference pattern in the phase locking and free regimes are presented in Fig. 5.

5. Conclusions

A system for maintaining a constant phase difference between two laser channels with a total output power of 60 W has been produced. We have demonstrated stable operation of a feedback system upon compensation of the phase difference in the laser channels in the case of thermal and mechanical influences on the active medium with a characteristic phasing time of 100 ms.

References

1. Andrusyak O., Smirnov V., Venus G., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **7195**, 71951Q (2009).
2. Uberna R., Bratcher A., Tiemann B.G., et al. *Appl. Opt.*, **49** (35), 6762 (2010).
3. Redmond S.M. *Opt. Lett.*, **36**, 909 (2011).
4. Yu C.X. et al. *Opt. Lett.*, **36**, 2686 (2011).
5. Lavan M. *Acta Phys. Pol., A*, **115**, 959 (2009).
6. Flores A., Shay T.M., Lu C.A., et al. *Proc. CLEO*, **SF3** (2011).
7. Wirth C., Schmidt O., Tsybin I., et al. *Opt. Express*, **17** (3), 1178 (2009).
8. August S.J. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **8237**, 823704 (2012).
9. Meng H., Sun T., Tan H., Yu J., et al. *Opt. Express*, **23** (17), 21819 (2015).
10. Yu C.X., Kansky J.E., Shaw S.E.J., Murphy D.V., Higgs C. *Electron. Lett.*, **42**, 1024 (2006).
11. Shay T.M. *Opt. Express*, **14**, 12188 (2006).
12. Volkov V.A., Volkov M.V., Garanin S.G., Dolgopolov Yu.V., Kopalkin A.V., Kulikov S.M., Starikov F.A., Sukharev S.A., Tyutin S.V., Khokhlov S.V., Chaparin D.A. *Quantum Electron.*, **43** (9), 852 (2013) [*Kvantovaya Elektron.*, **43** (9), 852 (2013)].
13. Volkov M.V., Garanin S.G., Dolgopolov Yu.V., Kopalkin A.V., Kulikov S.M., Sinyavin D.N., Starikov F.A., Sukharev S.A., Tyutin S.V., Khokhlov S.V., Chaparin D.A. *Quantum Electron.*, **44** (11), 1039 (2014) [*Kvantovaya Elektron.*, **44** (11), 1039 (2014)].
14. McNaught S.J., Komine H., Weiss S.B., Simpson R., Johnson A.M., Machan J., Asman C.P., Weber M., Jones G.C., Valley M.M., Jankevics A., Burchman D., McClellan M., Sollee J., Marmo J., Injeyan H. *Proc. CLEO* (Baltimor, MD, 2009) Paper CThA1.
15. Pyrkov Yu.N., Trikshev A.I., Tsvetkov V.B. *Quantum Electron.*, **42** (9), 790 (2012) [*Kvantovaya Elektron.*, **42** (9), 790 (2012)].
16. Duraev V.P., Nedelin E.T., Nedobyvailo T.P., Sumarokov M.A., Shishkov V.V. *Quantum Electron.*, **28** (4), 290 (1998) [*Kvantovaya Elektron.*, **25** (4), 301 (1998)].