Quantum Electronics **44** (11) 1039 – 1042 (2014)

FIBRE AND INTEGRATED-OPTICAL STRUCTURES

PACS numbers: 42.55.Wd; 42.60.Fc; 42.79.Hp
DOI: 10.1070/QE2014v044n11ABEH015626

Phase locking of a seven-channel continuous wave fibre laser system by a stochastic parallel gradient algorithm

M.V. Volkov, S.G. Garanin, Yu.V. Dolgopolov, A.V. Kopalkin, S.M. Kulikov, D.N. Sinyavin, F.A. Starikov, S.A. Sukharev, S.V. Tyutin, S.V. Khokhlov, D.A. Chaparin

Abstract. **A seven-channel fibre laser system operated by the master oscillator – multichannel power amplifier scheme is the phase locked using a stochastic parallel gradient algorithm. The phase modulators on lithium niobate crystals are controlled by a multichannel electronic unit with the microcontroller processing signals in real time. The dynamic phase locking of the laser system with the bandwidth of 14 kHz is demonstrated, the time of phasing is 3 – 4 ms.**

Keywords: *phase locking, fibre laser, stochastic parallel gradient algorithm.*

1. Introduction

A maximal energy and brightness of a laser source are limited by the possibilities of a particular active medium. If these possibilities are fully utilised, then a further increase in energy and brightness can be efficiently provided by summing radiation from several channels. Most promising seems the creation of multichannel laser systems in the master oscillator (MO) – parallel power amplifier geometry, with mutual phase locking of radiation in the channels [1]. There is a variant of coherent phase summation related to phase detection [2]. Its advantage is that the time of phase locking is independent of the number of channels, and the drawbacks are a complicated architecture of the system and high sensitivity to noise. These facts stipulated an interest to the approaches that are simpler to realise without measuring relative or absolute phases, for example, the iterative algorithm of stochastic parallel gradient descent (see, e.g., [3, 4]).

In the present work, the active phase locking of the seven-channel fibre laser system in the geometry 'MO – parallel power amplifiers' has been performed by using the stochastic parallel gradient (SPG) algorithm [5], which, similarly to the stochastic parallel gradient descent algorithm, is based on the principle of parallel voltage application across the phase and stochasticity modulators at a first stage of iteration. The SPG algorithm is a two-stage iterative procedure and under the condition of optimised parameters it gives the possibility to gain the axis brightness of multichannel radiation at each iteration step [6]. In [7], we performed dynamic phase locking of a sixteen-channel laser beam formed from radiation of a MO without amplification. The present work is aimed at the experimental demonstration of dynamic active SPG phase locking of the laser system comprising seven fibre amplifiers.

2. Experimental

The scheme of the experiment on phase locking of a seven-channel fibre laser is presented in Fig. 1. A two-stage master oscillator (*1*) (the wavelength is $\lambda = 1064$ nm) comprises a single-mode diode laser (*2*) and a fibre ytterbium pre-amplifier (*4*) pumped by a diode (*3*). The ytterbium pre-amplifier is a fibre with two coaxial cores in a single envelope. The outer passive multimode core (with a diameter of 50 μm) is used for introducing pump radiation. The other core of diameter 4 μm is an active single-mode one doped with Yb^{3+} ions. The length of preamplifier fibre is approximately 15 m. The width of the MO radiation line measured by a fibre ring interferometer is 2.5 MHz. The output MO power is 150 mW, and the degree of polarisation is 0.98.

The system for splitting radiation of the master oscillator to amplifiers (*6*) consists of three splitting cascades. The first cascade splits MO radiation into two channels, the second cascade – into four channels, and the third cascade – into eight channels. One channel has not been used in the experiment. The splitting coefficient of each cascade at $\lambda = 1064$ nm is 50/50. After the splitting system, radiation from each channel passes to fibre amplifiers (8) which are similar to a pre-amplifier (*4*) employed in the MO. All the amplifiers are pumped by a laser diode (*15*) of power 9 W through a multi-channel splitter (*7*). The gain of each amplifier is equal to 8 and the power of output summed radiation is approximately 1 W.

The amplified radiation is collimated and passes to a phase modulators (*10*) made of the Z-cut lithium niobate crystal with electrodes deposited to its lateral surfaces. The linear dimensions of the modulators are 4×4×45 mm. Their operation is based on the transverse electro-optical effect in the regime of phase modulation.

Radiation from the phase modulators passes to seven hexagonal-packed lenses fixed in a metal holder. After the lenses radiation consists of seven plane-parallel beams. An experimental near-field image of seven laser beams is shown in Fig. 2. After collimation, radiation enters a two-lens system (*12*) (Fig. 1) with the equivalent focal length of 45 m. A diaphragm of diameter 0.8 mm is placed at the focus of the lens system. Radiation passed through the diaphragm is detected by a photodiode (*16*). Under these conditions the photodi-

---

M.V. Volkov, S.G. Garanin, Yu.V. Dolgopolov, A.V. Kopalkin, S.M. Kulikov, D.N. Sinyavin, F.A. Starikov, S.A. Sukharev, S.V. Tyutin, S.V. Khokhlov, D.A. Chaparin Russian Federal Nuclear Center 'All-Russian Research Institute of Experimental Physics', prosp. Mira 37, 607190 Sarov, Nizhnii Novgorod region, Russia; e-mail: wolf-87ph@yandex.ru

Received 15 July 2014
Kvantovaya Elektronika **44** (11) 1039 – 1042 (2014)
Translated by N.A. Raspopov

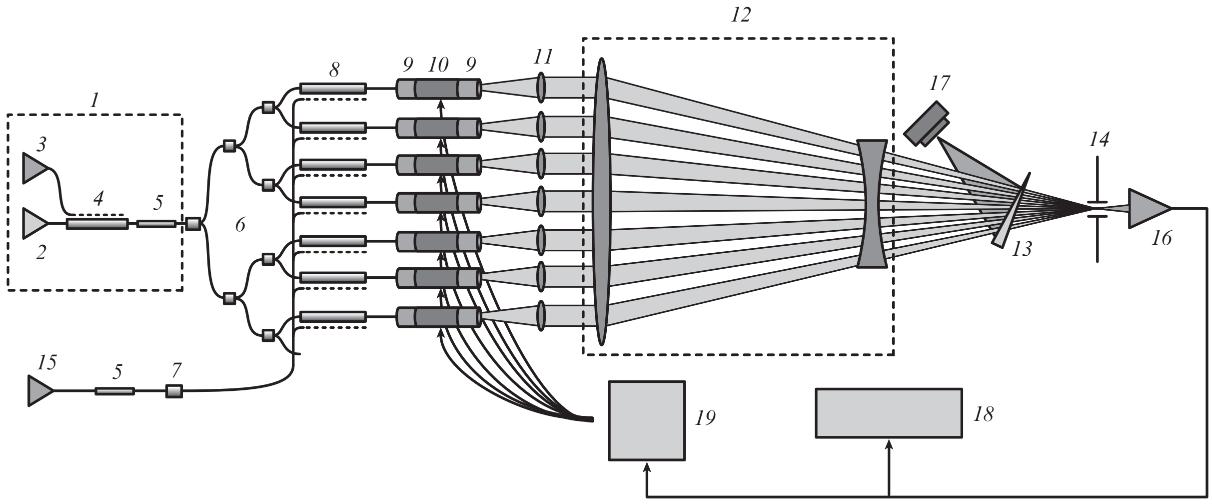

Figure 1. Scheme of the experiment on phase locking of the seven-channel fibre laser: (*1*) MO; (*2*) single-mode laser; (*3*) diode for pumping pre-amplifier; (*4*) pre-amplifier; (*5*) insulators; (*6*) system for radiation splitting; (*7*) multichannel splitter; (*8*) amplifiers; (*9*) collimators; (*10*) phase modulators; (*11*) lens assembly; (*12*) two-lens system; (*13*) wedge; (*14*) diaphragm; (*15*) diode for pumping amplifiers; (*16*) photodiode; (*17*) CCD-camera; (*18*) oscilloscope; (*19*) control unit for phase modulators.

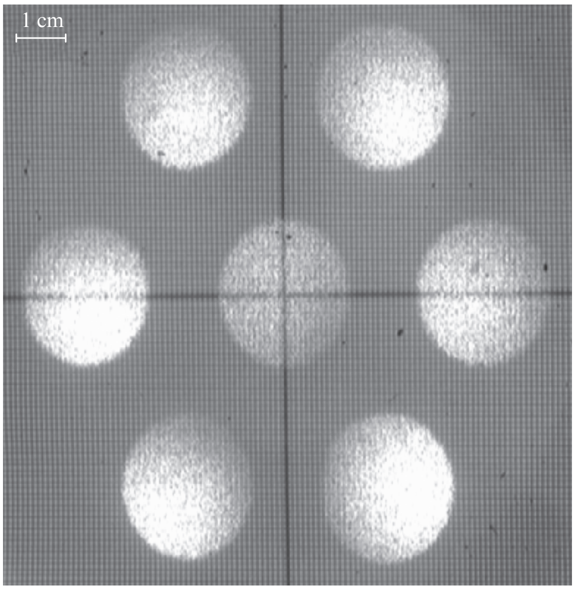

Figure 2. Experimental near-field radiation pattern of seven laser beams.

ode detects the power of seven-channel radiation in the angle of 0.017 mrad. A part of radiation reflected from a wedge (*13*) was recorded by the CCD matrix of a camera (*17*) also placed in the focal plane of the two-lens system. The signal from the photodiode is processed by a 32-bit microcontroller directly incorporated into the control block, which, according to the SPG algorithm, forms the voltages for the phase modulators. Thus, the phase control system is closed. The operation clock frequency of the phase system in the closed cycle was 14 kHz.

3. Results of experiments and calculations

The phase locking of radiation from amplifiers requires that the phases of output radiation in the channels were similar at all instants of time; however, they may vary in time. Obviously, the fast phase breakdowns of output MO radiation due to the finite width of its line are inessential because they are almost synchronously transferred through all amplifying channels at the coherence length specified. In addition to the constant phase difference in channels caused by different lengths of the optical path in various parts of the splitter and different lengths of amplifiers (see Fig. 1), there is a dephasing which randomly varies in time. This effect is explained by phase oscillations inherent in fibre amplifiers (phase noise) [8]. The main sources of phase oscillations are thermal processes, a mechanical resonance, acoustic and seismic noises. The most substantial phase oscillations are observed early at the start of laser operation and may reach the amplitude of up to 20λ in the bandwidth of up to 1 Hz. After establishing the regime of thermal equilibrium the maximal amplitude of phase oscillations in the amplifiers falls to $\lambda/3$. Note that optical inhomogeneities of the medium in which radiation propagates from the amplifier output to the detection unit may also result in additional dynamic dephasing.

The phase mismatch between separate amplifiers results in an instantaneous variation in the far-field intensity distribution of the multichannel beam. Examples of such distributions are shown in Fig. 3.

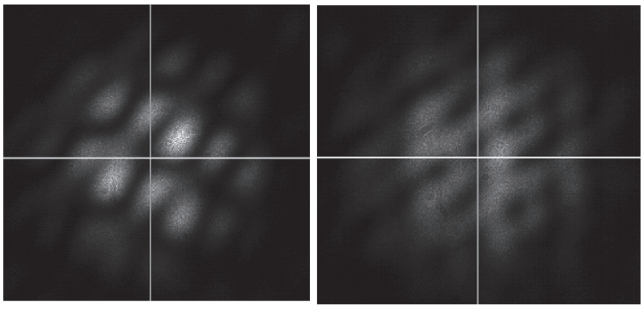

Figure 3. Examples of the far-field intensity distribution of radiation from seven fibre laser channels in the case of mismatched phases.

If the feedback of the phase locking system is switched on, then the photodiode (*15*) placed on the optical axis in the focal plane of the two-lens system detects the radiation power within a narrow solid angle and transfers the signal to the unit which controls the voltage across the phase modulators. By using the value of power as an objective function, the phase-locking system operating in a closed cycle according to the SPG algorithm should provide a permanent phase locking for radiations in all laser channels regardless of their initial phases. For attaining a maximal rate of convergence of the SPG algorithm, the optimal parameters have been determined [6, 7], which were used in experiments.

The images of calculated and experimental instantaneous far-field intensity distributions for seven phase matched channels of the fibre laser are shown in Fig. 4 along with the corresponding scans in one coordinate.

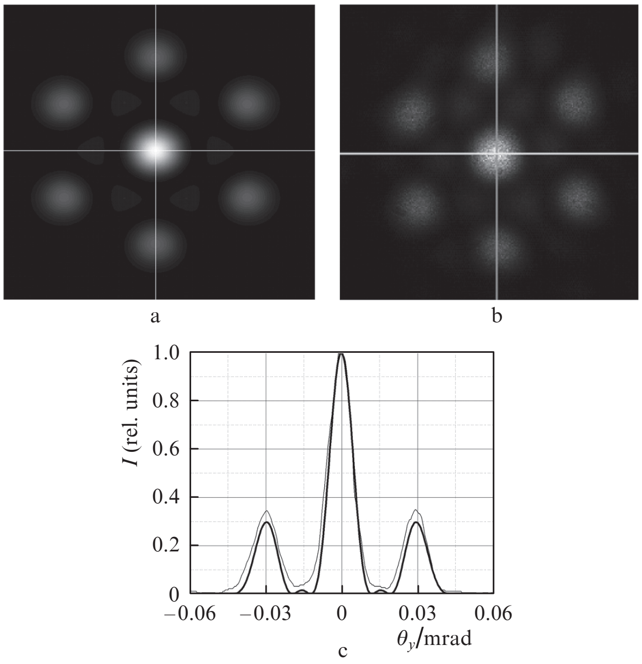

Figure 4. (a) Calculated and (b) experimental far-field intensity distributions I for seven phase-locked channels of the fibre laser and (c) the corresponding scans along the y coordinate (thin curve is the experiment, thick curve is the calculation).

The time dependence of the output photodiode signal is shown in Fig. 5 for the cases of feedback switching on/off and pause. The radiation intensity (a signal from the photodiode on the optical axis) in switching on the feedback (regime 'on' in Fig. 5) is on average seven times greater as compared to the case of dephasing and by 49 times greater than the intensity of a single channel. After stopping the feedback (regime 'pause' in Fig. 5) the voltages across phase modulators remain unchanged and the signal from the photodiode falls to a minimal value in a time lapse of 1–3 s, i.e., radiation again becomes dephased.

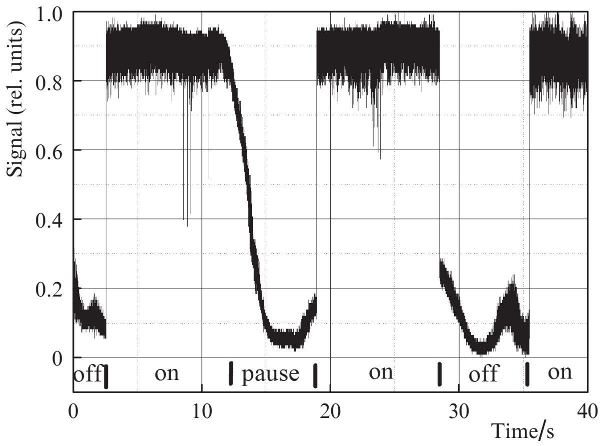

Figure 5. Output signal of the photodiode vs. time in the process of phase locking with the feedback switched on or off.

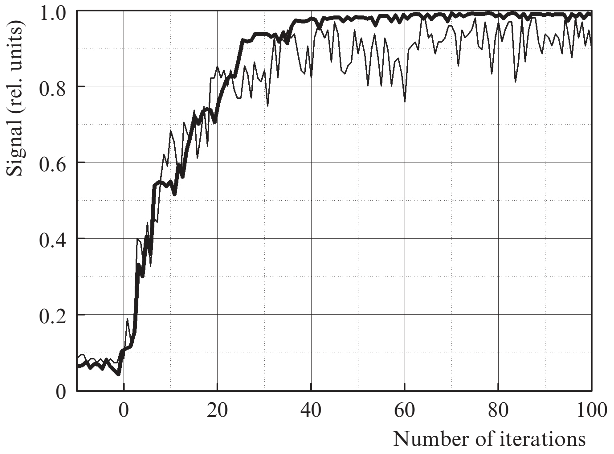

Figure 6. Experimental (thin curve) and calculated (thick curve) dependences of the output signal of photodiode on the number of iterations in the process of phase locking.

Experimental and calculated dependences of the output signal from the photodiode on the number of iterations of the SPG algorithm are shown in Fig. 6. The zeroth iteration in Fig. 6 corresponds to the instant $t = 2.562$ s (the feedback is switched on for the first time) in Fig. 5. In switching on the feedback, the signal reaches a maximal value after 21–27 iterations by the SPG algorithm and then keeps this value, which at the system bandwidth mentioned corresponds to the time lapse of 3–4 ms. The data obtained are confirmed by the calculation results given in [6, 7].

4. Conclusions

The phase locking of multichannel laser systems in the scheme 'single-channel MO – unit of parallel amplifiers' is studied by using the two-stage iterative SPG algorithm. The experimental test installation is made of a seven-channel fibre laser system ($\lambda = 1064$ nm) having the power of 1 W with the phase modulators based on a lithium niobate crystal and a microcontroller control unit. At the system bandwidth of 14 kHz the dynamic phase locking of radiation was demonstrated for the seven-channel fibre laser system. The time of phase locking was 3–4 ms. Data of the experiments well agree with calculation results.

The results obtained demonstrate that the employment of the SPG algorithm is promising for phase locking of the amplifying channels while constructing high-power continuous wave lasers in the 'single-channel MO–unit of parallel amplifiers' geometry.

References

1. Likhanskii V.V., Napartovich A.P. *Uspekhi Fiz. Nauk*, **160**, 101 (1990) [*Sov. Phys. Usp.*, **33**, 228 (1990)].
2. Anderegg J. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **6102**, 61020U 1-5 (2006).
3. Liu L. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **5895**, 58950P (2005).
4. Vorontsov M.A., Sivokon V.P. *J. Opt. Soc. Am. A*, **15**, 2745 (1998).
5. Garanin S.G., Manachinskii A.N., Starikov F.A., Khokhlov S.V. *Avtometriya*, **48**, 30 (2012).
6. 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. *Kvantovaya Elektron.*, **43**, 852 (2013) [*Quantum Electron.*, **43**, 852 (2013)].
7. 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. *Trudy RFYaTs VNIIEF*, **19**, 404 (2014).
8. Augst S.J., Fan T.Y., Sanchez A. *Opt. Lett.*, **29**, 474 (2004).