PACS numbers: 42.55.Wd; 42.60.Da
DOI: 10.1070/QE2006v036n01ABEH013038

Selection of optical modes in multichannel fibre lasers

D.V. Vysotskii, N.N. Elkin, A.P. Napartovich

Abstract. **The numerical simulation of radiation propagation in a multichannel fibre amplifier showed that the phases of input beams having the initial spread are equalised during the propagation of these beams due to the spatial filtration of the field by the structure of amplifying channels. The nonlinear part of the refractive index affects the phase matching process to a lesser extent. An increase in the coupling between the channels enhances the self-organisation of the beams.**

Keywords*: fibre laser, multichannel systems, mode selection.*

Along with rapid progress in the development of high-power single-mode fibre lasers (an output power of 1.96 kW was achieved at the beam quality parameter $M^2 = 1.2$ [1]), the search for constructions of multichannel fibres providing phase matching of radiation in all channels is being continued. It is expected that such an approach will provide an increase in the absorption of pump radiation and a decrease in the fibre length for the given output laser power. It is known that the maximum intensity achievable in the single-mode core of a fibre laser is limited by nonlinear SRS and SBS processes and decreases with increasing the fibre length. Therefore, the passage to a multichannel structure makes it possible, for the specified limiting intensity typical for a short fibre, to increase the output laser power proportionally to the number of channels.

However, the problem of phase matching in a multichannel fibre laser proves to be quite challenging. Due to the technological dispersion of properties of individual channels, the propagation constants in different channels are different, which prevents the generation of highly spatially coherent radiation. To provide the phase matching of channels having the dispersion of parameters, a strong optical coupling is required. To produce such coupling in a dense structure consisting of single-mode cores, the field outside the cores should be of the same order of magnitude as the field inside them. This condition was fulfilled in the construction containing seven single-mode microchannels forming a hexagonal lattice [2]. The authors of [2] reported the increase in the spatial coherence of a total field with increasing the pump power. In this case, the field distribution in the far-field zone corresponded to the total emitting aperture. This effect was interpreted [3] by solving numerically a system of equations for coupled modes as the result of nonlinear self-organisation of radiation from individual microchannels.

The traditional theoretical approach based on the expansion of the total field in modes of individual channels (coupled-mode equations) is valid only for a weak coupling [4]. In the case of strong optical coupling, direct numerical methods should be used. We developed a package of programs in the approximation of scalar and paraxial optics for calculating the propagation of radiation in a multichannel fibre laser, which is based on the method of splitting over diffraction and refraction processes taking into account the nonlinear response of a medium and amplification [5]. In this paper, this program package is used to simulate the propagation of radiation in a multichannel fibre studied experimentally [2].

The parameters of individual channels in a laser experiment inevitably differ from each other, resulting in the different propagation constants in them. As the first step for estimating the possible effect of the field self-organisation in a system of microchannels, we considered the propagation of radiation beams with random phases at the input of an amplifier with identical channels. Such a formulation of the problem corresponds to paper [3], allowing a comparison of the results of direct simulation with calculations based on the model of coupled modes. Figure 1 shows the profile of the refractive index of an ytterbium-doped fibre. The radius of each of the seven microchannels is 3.5 μm, the refractive-index jump is $\Delta n = 2.57 \times 10^{-3}$, corresponding to the waveguide parameter $V = 1.73$, and the distance between the centres of channels is 10.5 μm. The gain saturation was describe by the Rigrod formula [6] $g = g_0/(1 + I/I_s)$. The saturation intensity $I_s = 64.4$ kW cm^{-2} and the coefficient of quadratic nonlinearity of refraction $n_2 = 2 \times 10^{-12}$ cm^2 W^{-1} were taken from [3, 7] for the wavelength 1.1 μm. Note that the nonlinear part of the refractive index in an ytterbium-doped fibre is caused by the difference of polarisabilities of Yb^{3+} ions in different electronic states. To simplify calculations, the real complicated dependence of the refractive index on the field intensity determined by the level population kinetics is replaced by its qualitative quadratic dependence on the field amplitude. The value of n_2 presented above corresponds to the pump intensity 48.2 kW cm^{-2} [3]. We neglected the pump depletion in our calculations.

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Received 12 September 2005; revision received 13 October 2005
Kvantovaya Elektronika **36** (1) 73 – 75 (2006)
Translated by M.N. Sapozhnikov

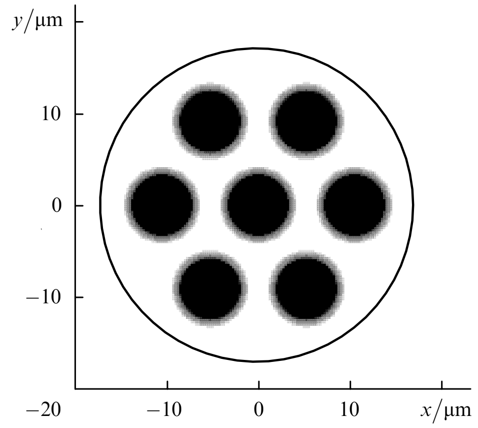

Figure 1. Level lines of the refractive index for a seven-channel fibre amplifier. The white background corresponds to the refractive index of the first cladding, the dark one – to the refractive index in microchannels.

It was shown that when seven identical beams, which are guided modes of individual channels, were coupled into a passive structure, a regime of beatings of two radial modes with a spatial period of 2 mm was established. A strong coupling in this system is illustrated by the ratio of radiation powers inside and outside fibre cores, which is equal to 0.62 : 0.38. The introduction of random phases of injected beams also results in excitation of other transverse modes.

We studied the process of in-phase mode separation from the initial set of seven input beams of the same intensity equal to $1.3I_s$ with a random phase distribution. At such an input intensity, a greater part of the fibre operated in the strong saturation regime. To determine the factors resulting in the formation of a plane wave front, we performed calculations for a random fixed phase sample (with the dispersion $\sigma_0 = 0.3$ rad) for different relations between parameters g_0 and n_2. In the main variant, $g_0 = 0.26$ cm^{-1} corresponds to the same pump intensity 48.2 kW cm^{-2} as for $n_2 = 2 \times 10^{-12}$ cm^2 W^{-1} [8]. In addition, we performed calculations in which the values of g_0 and n_2 were set to zero by turn.

Figure 2a shows the far-field intensity distribution for the input beam. The angular radius of the central peak estimated at the $1/e^2$ level by neglecting the side lobes is 45 mrad. The far-field intensity distribution after amplification over the length $L = 6$ m taking the nonlinear refraction into account is shown in Fig. 2b. The side lobes are now considerably weaker, which demonstrates the phase matching of fields in the channels. In this case, the angular radius of the central peak at the $1/e^2$ level is 44 mrad.

Figure 3a presents the dispersion of field phases in core centres as a function of the amplifier length for $n_2 = 0$. The oscillations of the phase dispersion are caused by beats of collective modes. The dispersion exponentially decreases on average with the decay length of 146 ± 15 cm. It follows from the calculation performed for $g_0 \neq 0$ and $n_2 \neq 0$ that the type of the dispersion behaviour does not change, while the decay length decreases to 120 ± 10 cm. In the absence of amplification for $n_2 \neq 0$, the decay rate of dispersion drastically decreases (Fig. 3b). Therefore, our calculations confirm the presence of self-organisation of light beams in the structure under study, but it is mainly caused by the filtration of the field by the aperture-inhomogeneous gain. This effect is explained in terms of collective modes by the

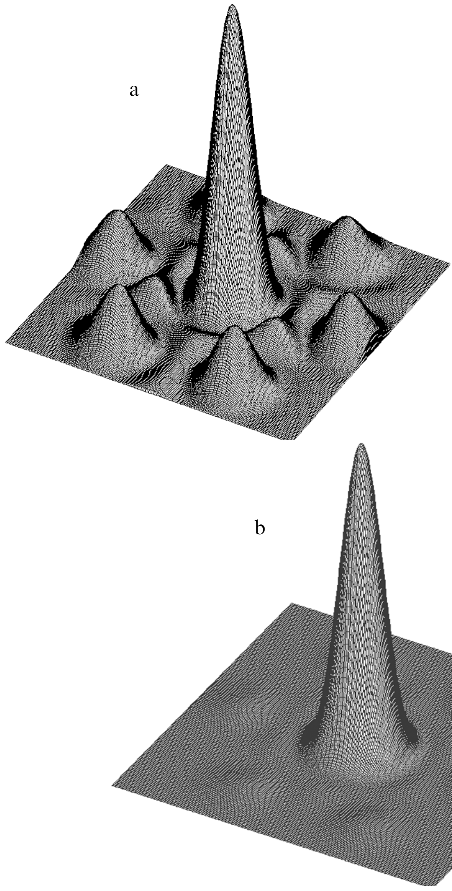

Figure 2. Far-field intensity distributions for the input (a) and output (b) beams of the amplifier for $L = 6$ m, $\Delta n = 2.57 \times 10^{-3}$, $g_0 = 0.26$ cm^{-1}, and $n_2 = 2 \times 10^{-12}$ cm^2 W^{-1}.

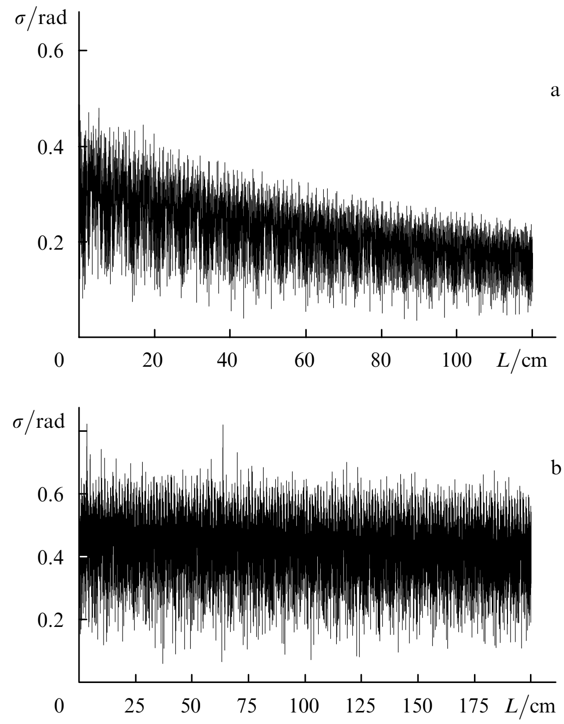

Figure 3. Dispersion σ of the field phases at the channel centres as a function of the amplification length L in the system with $g_0 = 0.26$ cm^{-1}, $n_2 = 0$ (a), $g_0 = 0$, $n_2 = 2 \times 10^{-12}$ cm^2 W^{-1} (b) and $V = 1.73$.

fact that the in-phase mode is most strongly overlapped with the gain profile, which results in its selection [4]. This conclusion contradicts to the prediction of the theory of coupled modes [3], where self-organisation appears only for $n_2 \neq 0$.

The coupling between channels can be increased by decreasing a jump of the refractive index. We performed calculations for $\Delta n = 1.27 \times 10^{-3}$ and $V = 1.22$ and found that the ratio of powers inside and outside the cores is 0.48 : 0.52, i.e., more than half the radiation is outside the amplifying cores. Our calculations showed that in this case the beats of radial modes disappeared and the phase dispersion in the absence of nonlinearity of the refractive index decays during the beam propagation much faster than in a multichannel fibre studied in [2] (Fig. 4a). The decay length of the phase dispersion is 46.9 ± 0.9 cm. Taking the nonlinear refraction into account, this length decreases to 41.4 ± 1.3 cm. Calculations performed for $n_2 = 2 \times 10^{-12}$ cm^2 W^{-1} and $g_0 = 0$ (Fig. 4b) predict the appearance of regular steady pulsations of the phase dispersion. Additional calculations showed that these properties were preserved when a random sample of the input field phases and of n_2 was changed.

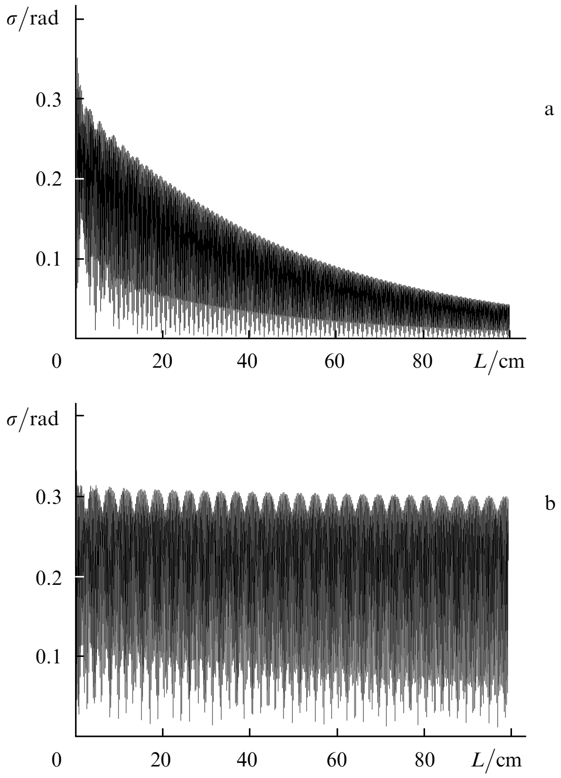

Figure 4. Phase dispersion σ as a function of the amplification length L in the system with $g_0 = 0.26$ cm^{-1}, $n_2 = 0$ (a), $g_0 = 0$, $n_2 = 2 \times 10^{-12}$ cm^2 W^{-1} (b) and $V = 1.22$.

Therefore, the direct numerical simulation of a seven-channel fibre amplifier with the channel geometry realised in the experiment [2] confirmed the presence of phase matching of the field in channels. However, our calculations have shown that this effect is mainly caused by the spatial filtration of collective modes by the gain in microchannels. Nonlinearity appearing upon self-focusing enhances somewhat phase matching only in the presence of amplification.

Acknowledgements. This work was supported by a grant RI-112/001/593 and the Russian Foundation for Basic Research (Grant No 02-02-17101).

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