Far - field modelling of a multicore optical fibre

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Abstract—In the paper the phase – locked emitters in multicore optical fibres for high power fibre lasers are presented. The influence of normalized frequency and diameters of the cores on the shape of the pattern in the Fraunhofer diffraction region has been analysed. The highest amount of energy conducted in the supermode is obtained at possibly large diameters of the cores and at possibly low value of normalized frequency.

Common application of semiconductor lasers as optical pumps and the development of the technology of forming optical fibres doped with rare-earth ions observed recently, has enabled to construct high-power fibre lasers. Because of their distinctive properties, such as: high amplification, low excitation threshold, high efficiency, excellent quality of the laser beam and no necessity of cooling (except for extreme cases) lasers of the above type are the subject of extensive research. Besides, recent progress in that field resulted in applying them as one of the basic structures of solid-state lasers [1-6]. The ability to accumulate energy by an active medium depends on its volume and concentration of an active dopant. Unfortunately, both parameters are limited by technological conditions. In the case of active fibres designed for the construction of pulse radiation sources (mainly in the generation regime of nanosecond) the reduction of numerical aperture in order to increase the core diameter while preserving the condition of single mode operation, leads to considerable emission of energy accumulated in the core to the cladding. This is caused by the phenomenon of spontaneous emission [1].

Double-clad multi-core optical fibres open the door to constructing short-length high-power fibre lasers. In fibres of this type the accumulated number of active dopant ions is significantly greater than in a classical single-core optical fibre. This enables to increase the ability to accumulate energy by an active medium, thus facilitating the N-fold reduction of the fibre length (where N is the number of cores), necessary to absorb pumping radiation. The basic problem of such a structure is, however,the low quality of a laser beam. Radiation intensity and beam divergence in such a case change proportionally to the number of emitters. If the radiation generated in particular cores is mutually coherent (phased), then the far-field diffraction pattern of a laser beam consists of central high-intensity and low-divergence peak and symmetrical side lobes with considerably lower radiation intensity. The angular divergence of the central peak is reduced in proportion to the number of emitters (elements of the matrix) generating mutually coherent radiation [2]. In an ideal situation, assuming that the phase difference between particular emitters equals zero, the intensity of the major peak rises with the square of the number of emitters. The simulations carried out by the authors aimed at checking the influence of parameters of multicore fibre, and in consequence, the far-field pattern.

The arrangement of cores in the analysed multi-core optical fibre is shown in Fig.1. Such a structure has been chosen because of the desired shape of the far-field pattern. Single-mode cores are located in a common cladding. The analysed optical fibre has the following parameters: diameter of the cores 2r = 10μm, normalized frequency V = 2.4, distance between the cores d = 10μm. The spatial distribution of emitted laser radiation for each core is described by a Gaussian function.

$$E_m(x, y, z=0) = A_m \exp\left[\frac{r^2}{w_0^2} + i\varphi_m\right] \qquad (1)$$

where: A_m – max. amplitude in m-*th* core, $r^2=(x-mx_d)^2+(y-ny_d)^2$ – cores coordinates w_0^2 - mode field radius, φ_m – phase of radiation in m –*th* core.

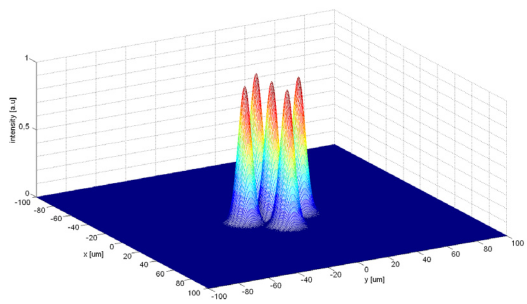

Fig. 1 Near field pattern of 5 –core optical fibre, V=2,4 2r=10 μm

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The far field diffraction pattern in the Fraunhofer diffraction region is determined according to equation (3).

$$Z = \iint U(x_1, y_1)[\exp(-i(x_0 x_1 + y_0 y_1)]dx_1 dy_1 \qquad (2)$$

$$U(x_0, y_0, z_0) = \frac{\exp(ikz)\exp\left[i\frac{k}{2z}(x_0^2 + y_0^2)\right]}{i\lambda z} \cdot Z \qquad (3)$$

where: $k = \frac{2\pi}{\lambda}$, λ - wavelength, (x_0, y_0) and (x_1, y_1) – points coordinates respectively - image plane and z = 0 plane.

In the Fraunhofer diffraction region, the field in the observation point can be calculated as the product of the Fourier transform of the input function distribution $U(x_1, y_1)$ and the phase function (4):

$$\exp\left[i\frac{k}{2z}(x_0^2 + y_0^2)\right] \qquad (4)$$

The Fraunhofer diffraction equation can be treated as the two-dimensional Fourier transform. The intensity of the far-field pattern is proportional to the square of the field amplitude averaged in time $|U(x_0, y_0, z_0)|^2$ [4]. The far-field distribution, assuming the lack of coherence between the radiation emitted from particular cores is shown in Fig. 2. The radiation phase from each core is random.

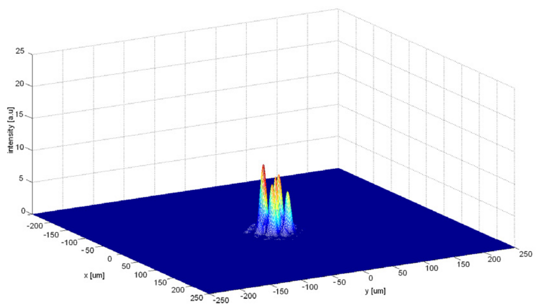

Fig. 2 Far field pattern of 5 –core optical fibre, random phases

In the far-field pattern, assuming that the radiation phase in each core is identical, the central peak intensity is much bigger than in the case of free running emitters (Fig. 3). It should be noted, however, that the laser spot diameter is inversely proportional to the number of cores. Moreover, the value of normalized frequency and the diameter of cores have a big influence on the far-field pattern in the multicore optical fibre (Fig. 3-6).

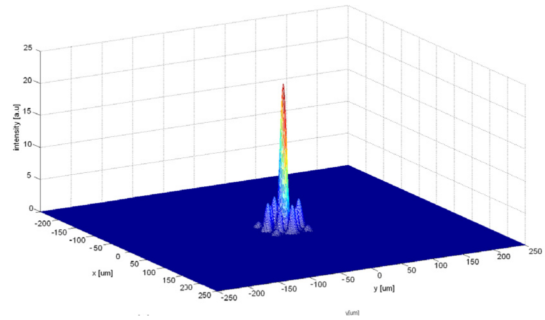

Fig. 3 Far field pattern of 5 –core phase - locked optical fibre, V=2,4 2r=10 μm

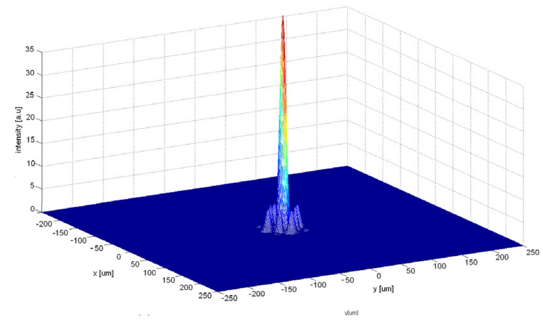

Fig. 5 Far field pattern of 5 –core phase - locked optical fibre, V=2,4, 2r=12 μm.

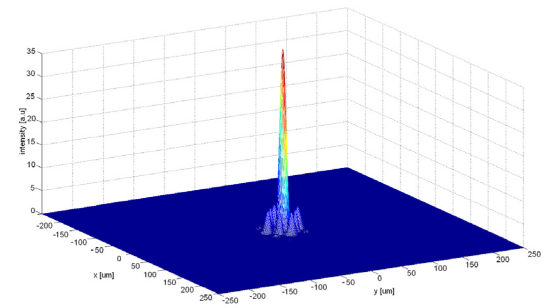

Fig. 4 Far field pattern of 5 –core phase - locked optical fibre, V=2, 2r=10 μm

A significant rise in the central peak (supermode) intensity in relation to the side lobes can be attained through the reduction of normalized frequency to the value equal V=2, as well as by increasing diameters of the cores to 2r=12μm (Fig. 4, 5). The far-field distribution with simultaneous change of both parameters (V=2, 2r=12 μm) is shown in Fig. 6. In comparison to optical fibres with parameters assumed beforehand (V=2.4, 2r=10 μm), it should be noted that both the central peak intensity and its relation to the radiation intensity of the side lobes are the highest. Besides, the amount of energy accumulated in the central peak is the largest of all the analysed cases.

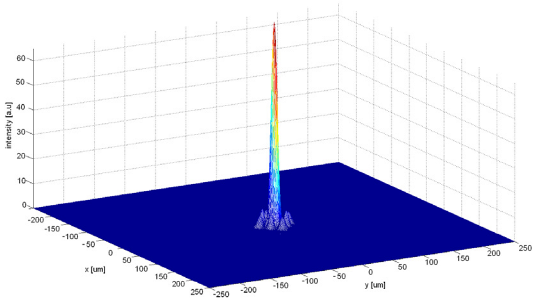

Fig. 6 Far field pattern of 5 –core phase - locked optical fibre, V=2, 2r=12 μm.

Assuming the mutual coherence of radiation generated in particular cores, the best quality of the beam in the Fraunhofer diffraction region is obtained at possibly large diameters of the cores and at a possibly low value of normalized frequency. These conditions, from the technological point of view, are difficult to attain because of the necessity to produce the core and cladding glasses with a very subtle difference in refractive indices. Coherent combining of a laser array can be realized by coupling between cores and as a result, by mutual injection-locking [5, 6].

Active multicore double-clad optical fibres with the cores generating mutually coherent radiation create new possibilities as far as the construction of high-power fibre lasers is concerned. This letter analyses the properties of a far-field diffraction pattern in the active 5-core optical fibre. Moreover, the influence of normalized frequency and diameters of the cores on the shape of the pattern in the Fraunhofer diffraction region has been analysed. Assuming the mutual coherence of radiation generated in particular cores, the best quality of the beam in the Fraunhofer diffraction region is obtained at possibly large diameters of the cores and at possibly low value of normalized frequency. Then, the amount of energy conducted in the supermode is the highest of all the considered cases. A low-divergence laser beam (supermode) in the far-field diffraction region is observed.

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