Abstract: We have realized and studied the fiber laser based on 4-core Yb-doped fiber and multimode Bragg grating as the input reflector. The lasing efficiency slope of 55% was measured. An investigation of the output emission has shown that the far-field pattern constitutes an interference picture. That allows us to conclude that the multimode Bragg grating provides phase locking of 4 lasers utilizing the different active cores. A coherent length of laser is longer than possible difference between optical ways of different active cores.

Fiber laser based on 4-core Yb-doped fiber and multimode Bragg grating

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1. Introduction

Fiber lasers are very attractive sources due to there compactness, good heat dissipation, high conversion efficiency, and high beam quality. However, the output power of lasers emitting in one transversal mode is limited by non-linear effects and by a laser damage of the fiber. The maximum achieved output power of such lasers is of approximately 1 kW [1]. Further growth of the output power can be obtained using the coherent combining of several lasers. In this case a brightness of the beam can be increased as N^2, where N – number of the lasers. At present several methods of the coherent combining were proposed. One of them is based on a multi-arm resonator of interferometric configuration. The combining occurs by using one of the fiber coupler ports to close the laser cavity [2,3]. It should be noted that the demonstrated output power obtained by this method is relatively small. The fiber coupler is a “weak” place of such schemes due to the presence of additional optical losses and bad heat dissipation. Then an application of this approach for high power laser seems to be improbable.

Another concept to scale lasers to high average output power consists in the application of multicore active fibers as an active medium. However advantages of the multicore lasers in comparison with a simple assembly of the fiber lasers can be shown only in a case of the phase locking between core oscillations. In this case a possibility of the coherent combining of beams emitted by the different cores is appeared. The main problem of the coherent combining consists in the phase locking realization. Phase locking of 18 cores by means of Talbot resonator was demonstrated.

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in [4]. Disadvantage of this work consists in the bulk element application. The coherent combining in an Yb-doped double-core fiber laser was observed in [5] due to the coupling via a biconical fused taper in a Michelson interferometric configuration. It is clear that in this scheme the taper is a “weak” place as well as in scheme utilizing the fiber coupler. Then the foundation of new methods of coherent combining is of current interest. In our work we study a laser based on 4 core Yb-doped fiber locked by Bragg grating written in the graded-index multimode fiber.

2. Fiber fabrication and laser design

To fabricate 4-core fiber we have used a preform with the Yb-doped core. The preform was cut on 4 parts. The pieces were milled to a shape close to 90 degrees sector containing the active core. All parts were collected and fused inside a silica tube. The fabricated fiber contained 4 cores disposed on a distance of 18 µm from the fiber center. Every core had the following parameters: the core diameter of 6 µm, the core-cladding index difference of 0.008, Yb ions concentration of approximately $5 \times 10^{19} \text{cm}^{-3}$. To provide pumping to the cladding, the fiber was coated by low index polymer providing a numerical aperture of 0.38. The absorption of the pump power at 976 nm was of approximately 5 dB/m. The fiber had the circular shape without any problem with the absorption efficiency.

The simplified laser scheme is shown in Fig. 1. The investigated laser consisted of the multicore active fiber with a length of 4 m and multimode Bragg grating written in graded-index fiber as input coupler. The grating had the resonance wavelengths around 1054 nm. Earlier we applied multimode gratings in schemes of the multimode [6] and single-mode [7] fiber lasers. In our case the multimode fiber had a core diameter of 50 µm. That allowed one to cover an area with the active cores by the Bragg grating. The cleaved end of the active fiber was used as the output reflector.

3. Laser characteristics

The realized laser exhibited a threshold power in a range of 1–1.2 W for different cores by pumping at the wavelength of 975 nm. Fig. 2 shows near field patterns for 3 values of the pump power $P_p$. One can see an increase of the number of laser channels with the growth of the pump power. This behavior can be explained by the slightly different reflection coefficient of the multimode Bragg grating for various mode groups. Fig. 3 illustrates the total output power versus the pump power. The efficiency slope of 55% was measured. This value is similar to results obtained in [6,7].
The output spectrum is unstable. It is varied between few certain spectral positions. A time of this variation can be estimated as ten seconds. Fig. 4 illustrates a typical output spectrum during its transmission between relatively stable spectral positions. It should be noted that the measurement was done in a random point of the far-field pattern.

An investigation of the temporal characteristics has shown a presence of the self-pulsing. Output power oscillations are shown in Fig. 5. The average pulse duration can be estimated as 3 $\mu$s, the period of oscillation – as 10 $\mu$s. To explain this dynamic behavior additional investigations should be performed.

4. Coherent properties

An investigation of the output emission has shown that the far-field pattern constitutes an interference picture. For the pump power exceeding the threshold insignificantly, the far field pattern represents the set of bands. The corresponding picture is shown in Fig. 6. An appearance of this structure can be explained by interference between beams emitted by two cores having the lowest lasing threshold. Under increasing of the pump power, the pattern becomes more complicate. It is a lattice-like. Fig. 7 illustrates this. Such behavior should be explained by interference between 4 laser beams.

The observation of interference patterns allows us to suppose that there is the mutual coherence of the emission from the various cores. To understand a reason of this phenomenon we have measured the emission spectrum for one of the cores with a resolution of 0.01 nm. The result is shown in Fig. 8. A width of the emission spectrum is less than 0.02 nm. This corresponds to a coherent length of 3 mm approximately. To estimate a difference of the optical ways for various cores we should take into account that the fiber was fabricated from one preform. Then, the main reason of possible optical ways difference consists in a parameters variation along the preform length. Usually this value is not higher than 10%. It means that for used fiber index difference and length, the optical ways difference is not more than 1 mm. That explains a formation of the interference patterns if all laser channels are phase-locked by the Bragg gratings.

It is more difficult to explain narrowing of the emission spectrum. In [7] the measured line width was of approximately 0.2 nm. Therefore we should believe the existence of a coupling between the cores. However the distance between the cores is too high for an optical interaction. We suppose that a weak coupling can appear inside multimode fiber between the Bragg grating and the splice with the active fiber. However this point requires a further investigation.
5. Resume

We have fabricated double-clad 4-core Yb-doped fiber. This fiber was used to build the fiber laser with the multimode Bragg grating as the input reflector. The lasing efficiency slope of 55% was measured. Observation of far-field interference patterns allows one to conclude that the multimode Bragg grating provides phase locking of 4 lasers utilizing the different active cores. Also we suppose the presence of a weak coupling between the cores providing by the multimode fiber.

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