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Use of single-mode pumping as a method for suppressing mode instability in fibre lasers by an example of a 100-W narrowband Yb-doped fibre laser

A.A. Surin, A.A. Molkov, T.E. Borisenko, K.Yu. Prusakov

Abstract. **A method for increasing the mode instability threshold in fibre lasers is proposed. It is used to develop a high-power narrowband (with a linewidth of ~0.1 nm) Yb-doped all-fibre laser with linearly polarised radiation and mode instability threshold exceeding 100 W.**

Keywords: *fibre laser, mode instability, linearly polarised laser radiation, cw laser.*

1. Introduction

Yb-doped fibre lasers have become an irreplaceable tool in both industry and research due to their record power, high reliability, and high beam quality [1]. To date, the output power of single-mode fibre lasers exceeds several kilowatts in the cw regime and several hundreds of kilowatts in the pulsed regime [2]. These lasers are implemented using different optical schemes, providing polarised and unpolarised radiation with different wavelengths in the range of 0.98–1.15 μm [3]. However, all-fibre lasers of this type have a rather large linewidth (above 1 nm). Until now, lasing with a relatively low (several hundreds of watts) power and narrow (~0.1 nm) linewidth directly in a few-mode active Yb-doped fibre has been impeded because of the mode instability (MI) [4].

At the same time, high-power narrowband (with a linewidth less than 0.1 nm) cw near-IR lasers are of interest, e.g., as promising pump sources for nonlinear conversion in nonlinear optical crystals; in particular, they can be used to implement second-harmonic generation and to produce high-power (several watts) cw radiation in the visible and UV spectral regions [5, 6]. A narrowband Yb-doped all-fibre laser is a suitable pump source specifically for generating green light with a wavelength close to 532 nm.

The purpose of this work was to develop such a laser. We proposed a method to increase the MI threshold when generating high-power narrowband radiation in an Yb-doped all-fibre laser based on a few-mode active fibre.

A.A. Surin, T.E. Borisenko NTO IRE-Polus, pl. Akad. Vvedenskogo 1, stroenie 3, 141190 Fryazino, Moscow region, Russia; e-mail: asurin@ntoire-polus.ru;
A.A. Molkov, K.Yu. Prusakov NTO IRE-Polus, pl. Akad. Vvedenskogo 1, stroenie 3, 141190 Fryazino, Moscow region, Russia; Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudnyi, 141701 Moscow region, Russia

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2. MI suppression

The effect of MI (energy transfer from the fundamental to higher modes) is observed in amplifiers and laser systems operating both in the cw regime with a narrow emission line and in the pulsed regime with a wide emission spectrum [7, 8]. MI was observed for the first time in fibres with a large core diameter (30–50 μm); however, a similar effect occurs also in few-mode active fibres having a core diameter of ~10 μm [4, 9]. MI, which leads to output power modulation [7–9], is a factor limiting high-power lasing with a narrow linewidth in fibre lasers and amplifiers.

Power transfer from the fundamental to higher modes is caused by the periodic refractive-index modulation (refractive-index grating), induced in the fibre by the radiation propagating through it [10]. This long-period grating is due to the interference between the fundamental and higher modes. Two mechanisms (thermal and inversion) are considered to be responsible for the grating formation [10, 11]. The MI threshold in an amplifier (the output power level at which beam distortions and output power instability begin to manifest themselves) depends on many parameters: lasing linewidth, level of backward-reflected signals, level of the amplifier input signal, and the polarisation state of radiation.

It was shown in [12, 13] that the MI threshold can be lowered by reducing the pump absorption efficiency. However, one must increase the active medium length in this case and thus lower the nonlinear effect thresholds. Therefore, the parameters (length and pump absorption efficiency) of the optical fibres used in high-power lasers must be optimised taking into account both the MI and nonlinear effects. For example, laser pumping was performed in [14] using semiconductor diodes of two types with different radiation wavelengths (975 and 915 nm) and a double-clad active fibre with a core diameter of 21 μm and numerical aperture NA = 0.066 (cladding diameter 400 μm, NA = 0.46); under these conditions, the pump absorption at the wavelength $\lambda = 915$ nm was 0.48 dB m^{-1}. In the case of diode pumping by only radiation with $\lambda = 975$ nm, MI was observed at an output power of ~1 kW. Under multimode diode pumping at $\lambda = 915$ nm, the output power was raised to 1.5 kW without MI occurrence; however, the laser efficiency decreased in this case. Under joint pumping by diodes emitting at wavelengths of 975 and 915 nm, MI-free 2-kW radiation was obtained in [14]; i.e., the MI threshold was increased by more than twice.

It should be noted that, using a purely single-mode active fibre, one can obtain high-power linearly polarised cw laser radiation with a narrow linewidth, free of MI. For example, a single-mode active fibre PLMA-YDF-10/125 (Nufem, United

States) with NA = 0.075 and core diameter 10 μm (the cutoff wavelength was 980 nm) was applied in [15] to obtain 100-W lasing at λ = 1120 nm with a linewidth of 0.2 nm. The MI effect is absent in the case of single-mode active fibre, because MI is caused by the interference of the fundamental mode with the higher, while the latter are not maintained in the fibre core. 100-W lasing with a linewidth of 0.26 nm at λ = 1098 nm in an ytterbium-doped fibre was obtained in [16]. The active fibre (core diameter d = 8 μm, NA = 0.11) used in that study, although being a few-mode one, had a cutoff wavelength of 1149 nm, which is close to the lasing wavelength (1098 nm). Since the error in determining the fibre parameters was not indicated, the cutoff wavelength could be smaller than the signal wavelength: for example, if the core diameter d is 7.6 μm instead of the declared value d = 8 μm, the cutoff wavelength is equal to 1092 nm. If NA is 0.1 rather than 0.11, the cutoff wavelength is 1045 nm; i.e., the fibre is single-mode. Nevertheless, even if higher mode generation could occur, it was not mentioned in [16]. Having measured the output power of the laser under study, the authors of [16] could in no way determine the achievement of MI threshold, because radiation was extracted directly from the few-mode active fibre, whereas no measurements of beam quality were performed and no oscillograms of output radiation were recorded. In addition, the radiation was unpolarised, and maybe the MI threshold was not reached for this reason.

When obtaining multikilowatt linearly polarised radiation in few-mode active fibres, MI was suppressed by packing fibres in a certain way [17, 18] and choosing an appropriate laser-diode pump wavelength [13]; this approach may be inconvenient or even inefficient in some cases.

In this paper, we propose a new method for suppressing MI in few-mode active ytterbium-doped fibres with NA > 0.1 and core diameters more than 10 μm (the cutoff wavelength exceeds 1300 nm): pumping of active fibre by single-mode radiation directly into the core. In the case of multimode pumping, the entire core of active fibre is uniformly pumped, and the gain for higher transverse modes is sufficiently high when the fundamental mode gain reaches saturation. As a result, the refractive-index grating (responsible for the MI), which is induced due to the interference between the fundamental and higher modes, has a large modulation depth. In our case, the active fibre is pumped mainly in the fundamental mode propagation region (depending on the overlap of the pump and signal fundamental modes); therefore, the inversion in the medium on the fundamental-mode tails will be much lower; correspondingly, the induced grating will have a smaller modulation depth.

The optical scheme of an ytterbium-doped fibre laser is presented in Fig. 1. The polarisation-maintaining GTWave fibre (IPG Photonics, United States), doped with Yb^{3+} ions, was used as the active medium. The fibre length was 10 m, and the light-guiding core diameter was 10 μm. Multimode pumping was performed by 975-nm semiconductor diodes. Narrow-band (reflection bandwidth less than 0.1 nm) gratings at λ = 1072 nm, written in a passive polarisation-maintaining single-mode fibre, matched to the fundamental mode, were placed in thermostats to match reflection spectra. Higher emission modes were de-excited at the welding junctions between the passive single-mode fibres and active few-mode fibre; i.e., these junctions played the role of mode filters. The cavity contained a fibre polariser, which provided linearly polarised lasing. Single-mode pumping was performed directly into the active fibre core by a linearly polarised beam

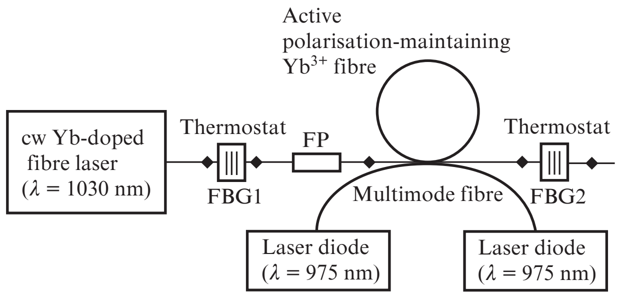

Figure 1. Optical scheme of a high-power narrowband Yb-doped laser generating at λ = 1072 nm: FBG1 is a high-reflective grating for λ = 1072 nm, FBG2 is a grating playing the role of an output mirror, and FP is a fibre polariser.

of single-mode ytterbium-doped fibre laser at λ = 1030 nm (NTO IRE-Polus, Russia).

3. Experimental results

When only diode pumping at λ = 975 nm was used, MI was observed at a laser output power of 1.5 W. The corresponding power oscillogram is shown in Fig. 2.

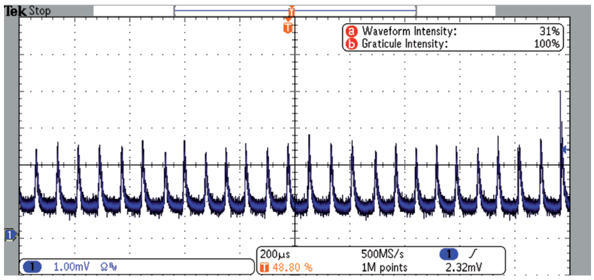

Figure 2. Oscillogram of the output power of a laser pumped by multimode radiation at λ = 975 nm. The output power is 1.5 W; the scan rate is 200 μs div^{-1}.

The periodic sequence of pulses against the cw signal background is a manifestation of MI. A further increase in the pump power leads to a decrease in the output power, which also indicates achievement of the MI threshold.

Pumping by a single-mode beam at λ = 1030 nm leads to an increase in the MI threshold: it could not be reached up to an output power of 50 W (a further increase in power was limited by the 1030-nm Yb-doped laser in use). The experimental results are presented in Fig. 3.

We obtained lasing at λ = 1072 nm with power of more than 50 W, efficiency of ~78%, and linewidth of 0.11 nm in a simple laser scheme (Fig. 1). In addition, in contrast to [14], we improve rather than deteriorate the laser efficiency in this case, because the quantum defect between the energies of pump photons and 'useful' lasing photons is reduced.

Since the single-mode pump power was limited, we used additional pumping by multimode radiation at λ = 975 nm in order to achieve the MI threshold; as a result, lasing with a power of more than 100 W and a linewidth of 0.15 nm was obtained.

The lasing oscillogram at P_{las} = 100 W is presented in Fig. 4. The MI threshold is achieved at this power, which

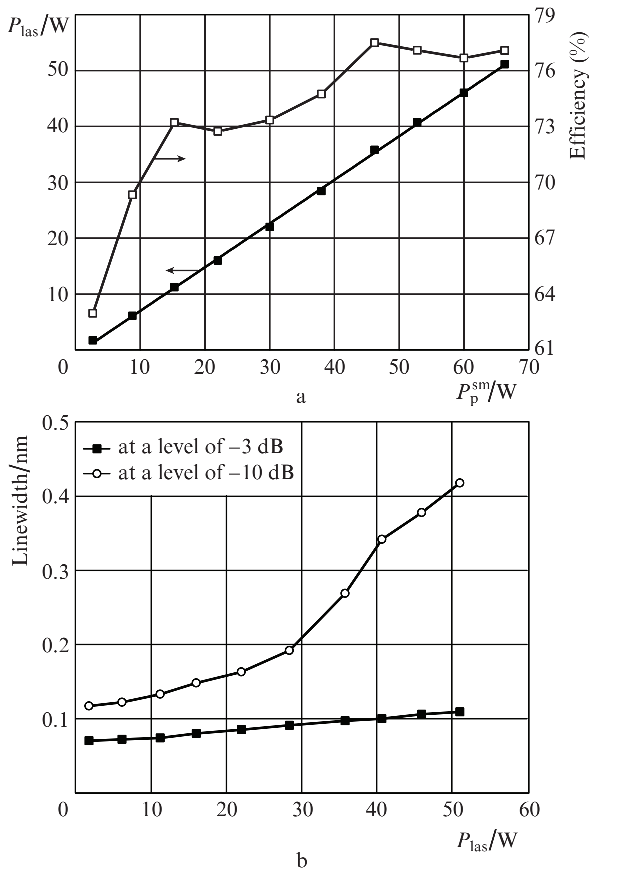

Figure 3. (a) Dependences of the laser output power P_{las} at λ = 1072 nm and the lasing efficiency on the single-mode pump power P_p^{sm} at λ = 1030 nm and (b) the dependence of the lasing linewidth on P_{las}.

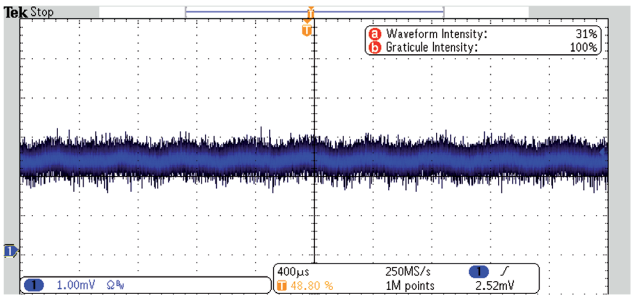

Figure 4. Oscillogram of the laser output power at P_{las} = 100 W; the scan rate is 400 μs div^{-1}.

manifests itself in the form of periodic output power oscillations with frequencies on the order of several kHz.

It was established that, in the case of joint use of laser diodes and a single-mode laser for pumping, the MI threshold depends on the single-mode pump power: the higher this power, the larger the MI threshold (Fig. 5).

Based on the results obtained, we developed an optimised version of a Yb-doped laser, in which use was made of an active 1.5-m-long Yb^{3+}-doped fibre and a higher power single-mode pump Yb-doped laser. The dependences of the laser output power and efficiency on the single-mode pump power are presented in Fig. 6.

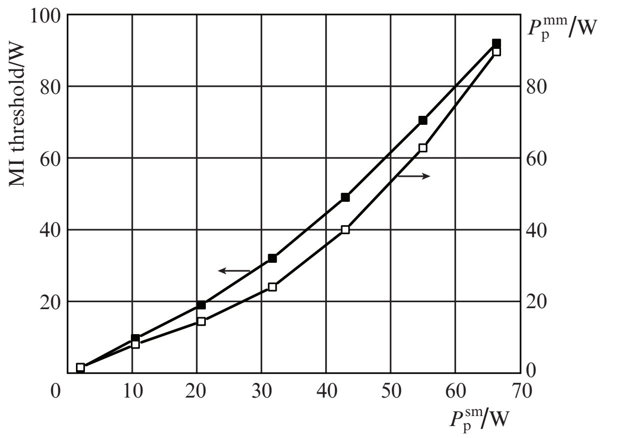

Figure 5. Dependence of the MI threshold on power P_p^{sm} in the case of joint use of laser diodes and single-mode laser for pumping: (filled squares) P_{las} values at which MI occurs and (open squares) values of power P_p^{mm} of additional multimode pumping required to achieve the MI threshold at a specified power P_p^{sm}.

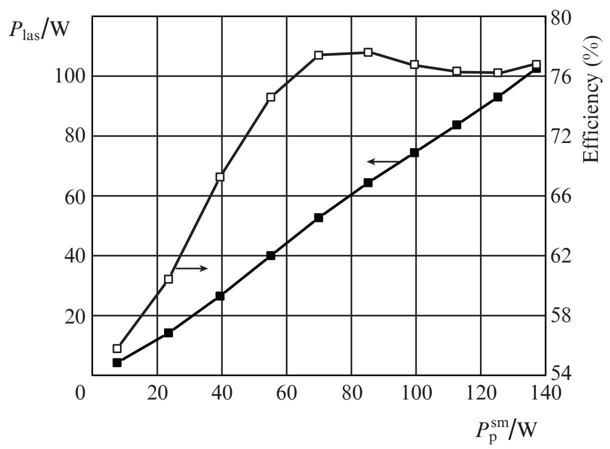

Figure 6. Dependences of the laser output power and efficiency on the single-mode pump power.

Figure 7 shows a beam cross section and the radiation intensity distribution along two orthogonal directions, measured at an output power of 100 W. The laser beam quality factor M^2 measured using a BeamMap2 profiler (DataRay, United States) was found to be 1.05. We also measured the degree of polarisation of the output (linearly polarised) radiation, which was found to exceed 99%. The ratio of the powers for two orthogonal polarisations was 22 dB. It was determined as follows: the beam was split by a calcite prism into two orthogonally polarised beams, after which power was measured in each beam.

4. Conclusions

A new method was proposed to suppress MI in ytterbium-doped fibre lasers based on few-mode active fibres. This method, which implies the use of a single-mode laser for pumping, significantly reduces the sensitivity of the MI threshold to the spectral radiation width and backward reflections. The MI threshold increases for the following reason: under single-mode pumping, population inversion is formed

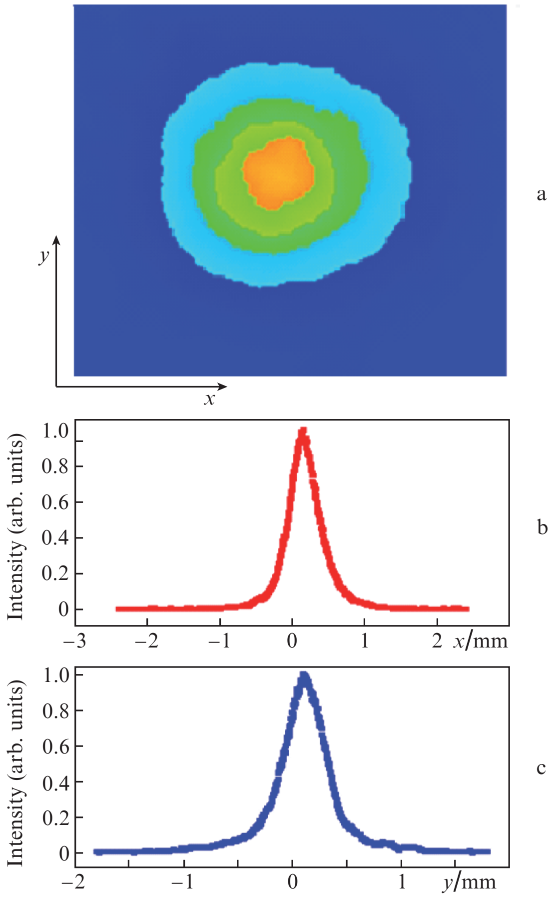

Figure 7. (a) Beam cross section at an output power of 100 W and (b, c) the radiation intensity distributions along the (b) x and (c) y axes.

mainly in the propagation region of the fundamental transverse signal mode. It should be noted that this should be valid for any types of fibre lasers and amplifiers based on few-mode active fibres, although experimental verification was not performed in this study. Based on this method, a cw ytterbium-doped all-fibre laser was developed, which generated single-mode linearly polarised radiation at λ = 1072 nm, with a power of more than 100 W and a linewidth of 0.15 nm; this is a promising pump source for second-harmonic generation in periodically poled crystals.

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