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FIBRE LASERS

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Mechanism of spontaneous switching of polarisation in an ytterbium-doped fibre laser

V.G. Voronin, Ya.V. Sya, O.E. Nanii, V.I. Khlystov

Abstract. **The regime of polarisation switching in a double-clad ytterbium fibre laser is studied experimentally and explained theoretically. It is shown that polarisation switching appears in lasers with the long active medium (no less than 20 m) when the pump slightly exceeds the threshold. The experimentally observed properties of spontaneous polarisation switching in the ytterbium fibre laser are explained by the competition of modes with orthogonal polarisations taking into account the polarisation-dependent saturation of amplification and losses.**

Keywords: *polarisation, switching, fibre laser.*

1. Introduction

The study of polarisation dynamics in ytterbium fibre lasers is of great practical and scientific interest due to wide possibilities of their practical applications. Simultaneous stationary generation of two orthogonally polarised modes is observed in a majority of fibre lasers [1, 2] but the regime of spontaneous switching of two orthogonal linearly polarised modes have been discovered only recently [3]. However, the switching mechanism was not explained in [3].

In this paper we studied experimentally in detail the polarisation dynamics of emission from an ytterbium fibre laser, determined the physical mechanism of polarisation switching and proposed the model describing the experimental results.

2. Experimental setup

Figure 1 shows the scheme of the experimental setup. We used a double-clad optical fibre as an active element of the laser, the single-mode core (of diameter $d = 5$ μm) of the fibre being doped with ytterbium. The internal (first) cladding had the square section of 120×120 μm and was surrounded with the external (second) circular cladding of diameter 200 μm. The concentration of ytterbium ions was 7.5×10^{19} cm^{-3}. The refractive index of the core was $n = 1.5$ and the difference in the refractive index of the core and internal cladding was $\Delta n \approx 0.01$. These conditions provided the single-mode operation regime of the laser. Taking into account the pump-radiation absorption by the core, the decay in the first cladding was 1.4 dB m^{-1}.

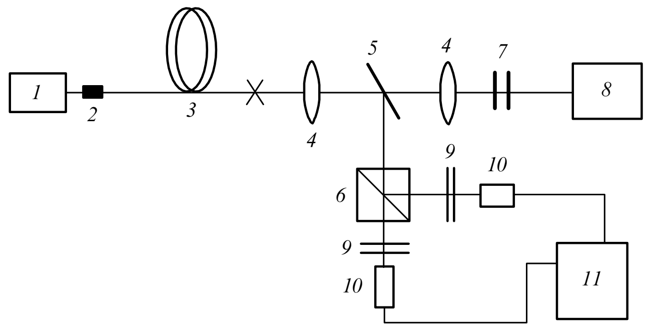

Figure 1. Scheme of the experimental setup: (*1*) diode pump laser; (*2*) fibre Bragg grating; (*3*) active fibre; (*4*) lenses; (*5*) beamsplitter; (*6*) polariser; (*7*) Fabry – Perot interferometer; (*8*) streak camera; (*9*) filters; (*10*) photodetector; (*11*) oscilloscope.

We used lasers of two types in experiments. The length of the active fibre in the first laser was 30 m and in the second one – 20 m. The lasing wavelength of the ytterbium fibre laser was 1081 nm. The ytterbium fibre laser was pumped by a 972-nm diode laser whose radiation was coupled into the first cladding of the optical fibre. As a highly reflecting mirror at 1081 nm we used the Bragg grating formed in the fibre core. The reflection coefficient of the grating at the wavelength of the Yb laser was 99 %. The fibre end served as the output mirror.

The output radiation of the fibre laser was collimated with the help of a lens. The collimated light beam was split into two by a beamsplitter: one beam was coupled to the Fabry – Perot interferometer to observe the spectrum and the other was incident on the polarisation prism. After propagation through the polarisation prism, the beam was again split into two beams whose polarisations were mutually orthogonal. Then, the beams were incident on the photodetectors. The polarisation lens was placed in the device, which provided smooth change in its orientation with an accuracy of 1°. Signals from photodetectors were coupled to an ASK-3151 digital two-channel storage oscilloscope and stored in the PC memory.

3. Experimental results

Our experiments have shown that both lasers have complex polarisation dynamics of emission. The most pronounced switching regime is observed in a laser with the active element of length 30 m. The average radiation power in this

V.G. Voronin, Ya.V. Sya, O.E. Nanii, V.I. Khlystov Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119992 Moscow, Russia; e-mail: editor@lightwave-russia.com

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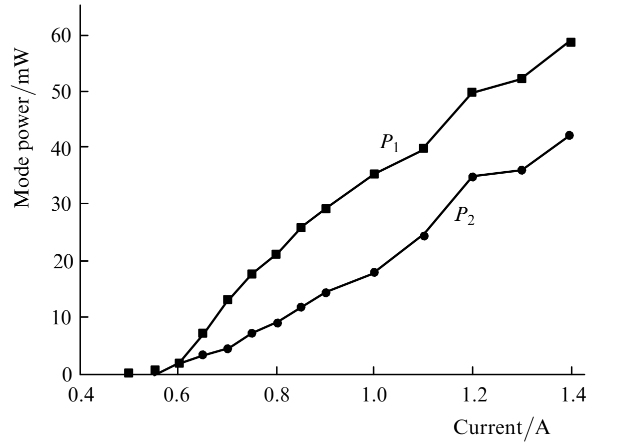

Figure 2. Dependences of the average output power of polarisation modes P_1 and P_2 on the pump current.

laser increases monotonically with increasing the pump power. The dependences of the average output power of different modes on the pump current at room temperature are shown in Fig. 2. The lasing thresholds and average powers of orthogonal linearly polarised modes were approximately the same.

The typical time evolution of powers in both orthogonal linearly polarised modes is presented in Fig. 3a (for a pump current of 1 A). One can see that lasing at every instant of time occurs predominantly on one polarisation component. Switching of lasing from one polarisation mode to the other occurs at irregular time intervals. Then, after some time, switching occurs again to the initial polarisation mode.

At a fixed pump power, the period between two subsequent switchings changes randomly, but the average time between switchings (we will call it the average switching period) is preserved. As the pump power is increased, the average switching period decreases, which is shown in Fig. 4.

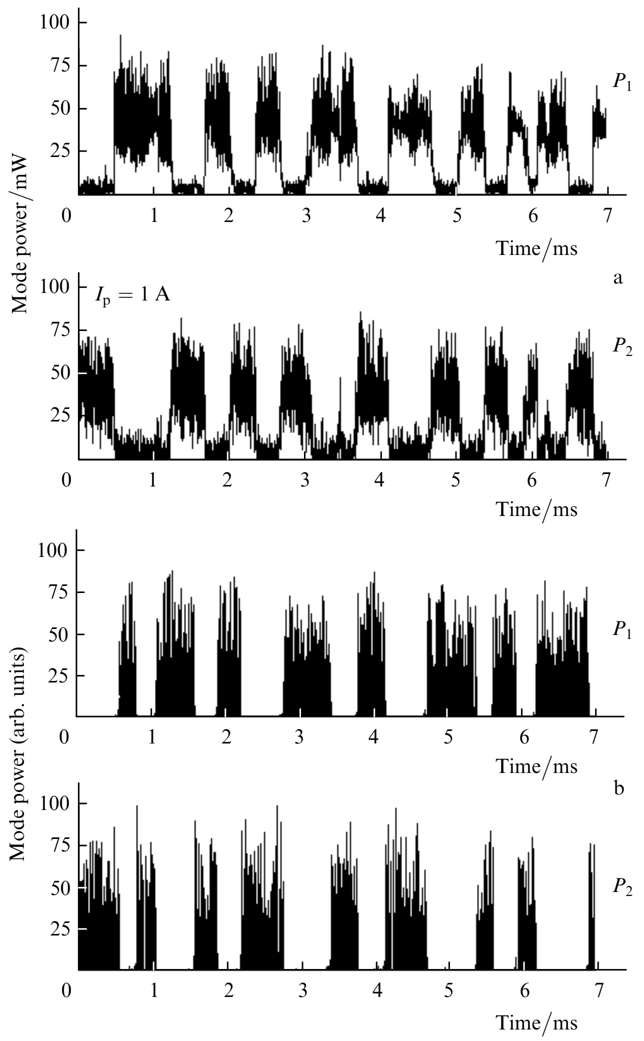

Figure 3. Time evolution of the radiation power of two orthogonal linearly polarised modes P_1 and P_2 obtained experimentally (a) and theoretically (b).

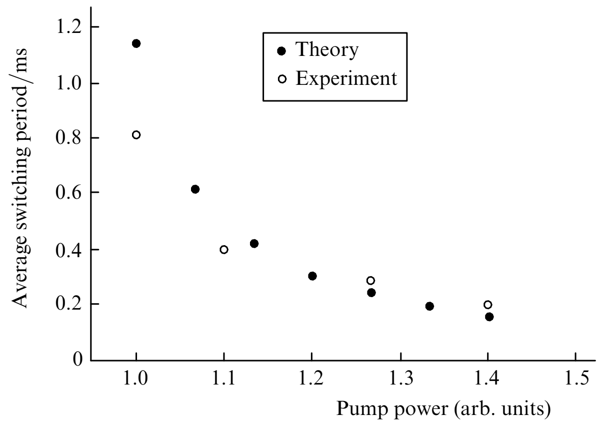

Figure 4. Theoretical and experimental dependences of the average period of polarisation switching on the pump power.

In a laser with the active medium of length 20 m, the switching regime is observed only in the limited region of the pump excess over the threshold. At some critical pump power in such a laser, the switching regime transfers to the stationary lasing regime of two polarisation modes.

4. Theory

The majority of dynamic models are based on the assumption that the eigenmodes of a laser resonator have the same polarisation and the active medium contains particles with equally oriented dipole moments. These models describe rather well the behaviour of many multimode solid-state lasers [1], but they simulate only stationary lasing regimes either with two polarisation modes or one, because it follows from them that the self-saturation coefficients exceed the cross-saturation coefficients. However, the regimes of polarisation switching and bistable regimes found experimentally [2–4] indicate that under certain conditions the reverse situation is possible when cross-saturation coefficients exceed self-saturation coefficients.

Following paper [1], we assume that two eigenstates of the fields exist, i.e. all generated modes are divided into two ensembles according to their polarisation (two polarisation modes). Because the cross section of the used double-clad fibre is symmetric, these modes are linearly polarised. They compete like usual longitudinal or transverse modes through the cross-saturation of the active medium [5]. Therefore, we will assume in the theoretical model that two orthogonal states of linear polarisation of the field exist.

A clad-pumped fibre laser can be considered as a device consisting of two parts: active (amplifier) and passive (absorber). The passive part of the fibre plays the role of the negative feedback or a bleaching filter.

The dynamics of two-channel lasers was earlier described by using the simplest balance equations, as in [6]. In the case when the pump power substantially exceeds the lasing threshold and all the fibre is treated as an active medium, the balance approximation equations, taking into account the interaction of linear polarisation through saturation of the inverse population of orthogonal polarisation, have the form

$$\frac{dI_i}{d\tau} = (n_i - 1)I_iG_i + \delta_i,$$
$$\frac{dn_i}{d\tau} = \alpha_i - n_i\Big(1 + \sum \xi_{ij}I_j\Big), \qquad (1)$$

where $i,j = 1, 2$; $I_{i,j}$ are the normalised intensities of two orthogonal linearly polarised modes; n_i are normalised gains (or population differences) of the active medium; α_i are the average unsaturated normalised gains of the active medium (average excess of the pump over the threshold in corresponding polarisation modes by assuming that lasing in the resonator is absent); G_i are parameters equal to the ratio of the relaxation time of the inverse population to the field decay time in resonators of the corresponding polarisation modes; ξ_{ij} are cross-saturation and self-saturation coefficients; δ_i are random functions characterising the contribution of spontaneous emission to lasing (they are introduced phenomenologically).

System of equations (1) for $\delta_i = 0$ has four equilibrium states, which are singularities

$$\bar{I}_i = 0, \quad \bar{I}_i = \frac{\alpha_i - 1}{\xi_{ij}}, \quad \bar{I}_j = 0,$$

$$\bar{I}_i = \frac{(\alpha_i - 1)\xi_{jj} - (\alpha_j - 1)\xi_{ij}}{\xi_{ii}\xi_{jj} - \xi_{ij}\xi_{ji}}.$$

To determine the type of singularities, we will study the stability of solutions of system (1) in the vicinity of each singularity for small deviations: $\delta I_i = I_i - \bar{I}_i$, $\delta n_i = n_i - \bar{n}_i$. The dependence of emission intensities for two polarisation modes on the pump is determined by the self-saturation and cross-saturation coefficients: if the cross-saturation coefficient is smaller then the self-saturation coefficient, the output radiation in both orthogonal polarised modes increases with increasing the pump power. However, if the cross-saturation coefficient is larger than the self-saturation coefficient, generation of one of two polarised modes is suppressed. The experimental and theoretical studies have shown that $\xi_{ii} > \xi_{ij}$ in solid-state lasers [6]. In this case, the solution of (1) is the simultaneous generation of two polarised modes. To explain the experimentally observed switching between polarisations, we should take into account the spatial distribution of the inverse population along the active medium. In addition, at normal temperature the resonance absorption of radiation is observed in an ytterbium fibre laser in the absence of pumping.

Taking the resonance absorption into account, we obtain a system of equations describing the interaction of two orthogonal linearly polarised modes in a double-clad fibre laser:

$$\frac{dI_i}{d\tau} = [x_in_i + (1 - x_i)m_i - 1]I_iG_i + \delta_i,$$
$$\frac{dn_i}{d\tau} = \alpha_i - n_i\Big(1 + \sum \xi_{ij}I_j\Big), \qquad (2)$$
$$\frac{dm_i}{d\tau} = m_{i0} - m_i\Big(1 + \sum \chi_{ij}I_j\Big),$$

where m_i are normalised absorption coefficients of the passive medium; m_{i0} are average unsaturated normalised coefficients of the passive medium; χ_{ij} are the absorption cross-saturation and self-saturation coefficients; x_i is the ratio of the pumped length of the active fibre to the total length. We assume below that all the parameters are symmetric with respect to i, j.

Parameters α_i, m_{i0}, and x_i depend on the pump. Their values are determined from the expressions:

$$\frac{\partial I_p(z)}{\partial z} = -\left[\frac{b^2}{a^2}\sigma_p\Delta N_{th}\frac{1}{f_0 + f_2}\left(\Delta N(z) - \frac{\Delta N_0}{\Delta N_{th}}\right) + \beta_pI_p\right], \qquad (3)$$

$$\Delta N(z) = \frac{[I_p(z)/Z_0Z_2](1 - Z_0f_0)N_t + \Delta N_0}{1 + [(Z_0 + Z_2)/Z_0Z_2]I_p(z)}\frac{1}{\Delta N_{th}}, \qquad (4)$$

$$\alpha_i = \alpha_j = \frac{1}{x}\int_0^x \Delta N(z)dz, \quad m_{i0} = m_{j0} = \frac{1}{L - x}\int_x^{L-x} \Delta N(z)dz,$$

$$\Delta N(x) = 1, \quad x_i = x_j = x,$$

$$\Delta N_{th} = \frac{n}{\sigma_s\tau_c c}, \quad f_0 = \frac{\exp(-\Delta E_{0r}/kT)}{Z_0},$$

$$f_2 = \frac{\exp(-\Delta E'_{0r}/kT)}{Z_2}, \qquad (5)$$

where

$$Z_0 = \sum_{r=1}^{m}\exp(-\Delta E_{0r}/kT); \quad Z_2 = \sum_{r=1}^{m}\exp(-\Delta E'_{0r}/kT);$$

ΔE_{0r}, $\Delta E'_{0r}$ are the energy differences between laser sublevels r and the lowest sublevel in the system of ytterbium sublevels $^2F_{7/2}$ and $^2F_{5/2}$; I_p is the normalised pump intensity; ΔN_0 is the initial density of the inverse population of sublevels in the equilibrium state; ΔN is the normalised value of the inverse population; σ_p is the cross section of the induced transition between pumped levels; σ_s is the cross section of the induced transition between laser levels; τ_c is the decay time of photons; N_t is the concentration of ytterbium ions; c is the speed of light in free space; L is the active-medium length; n is the refractive index of the active medium; b is the core diameter; a is the aperture of the internal fibre cladding; β_p are all nonresonance pump losses in the active medium; k is the Boltzmann constant; and T is the absolute temperature.

5. Discussion

Model of the ytterbium fibre laser (2) takes into account two type of mode interaction through the active medium. The behaviour of the solution of system (2) can be analysed by the methods of the theory of nonlinear oscillations. Our analysis has shown that the polarisation dynamics is related to the polarisation dependence of saturation in the ytterbium fibre.

The numerical experiment has shown that the region of existence of the polarisation switching regime strongly depends on the relative length of the active fibre, the pump power and the temperature of the active fibre. As the pump is increased, the pumped part of the active fibre increases while the unpumped part of the fibre decreases, the average period between polarisation switchings decreasing as well. As the pump is further increased, the polarisation switching is not observed: the stationary regime of generation of two polarisation modes is established. Only small out-of-phase power oscillations of polarisation modes appear in this regime.

Note that random fluctuations of the coupling coefficients lead to random polarisation switchings. Apart from experimental dependences, Figs 3b and 4 show theoretical dependences of the average period of polarisation switching on the pump power and the time evolution of radiation power of two orthogonal linearly polarised modes. The value m_{i0} of unsaturated absorption substantially affects the period of polarisation switching.

Our preliminary experiments have shown that at room temperature two-mode oscillation was observed in the laser with the active medium of length 10 m, with the length of 30 m – the regime of polarisation switching and with the length of 20 m the character of switching depended on the pump power. The region of polarisation switching increased with increasing temperature. The comparison with the experiment has shown (see Figs 3 and 4) that model (2) described correctly the polarisation dynamics of the double-clad ytterbium fibre laser.

Therefore, spontaneous switching of polarisation observed in experiments with the double-clad ytterbium fibre laser is explained by the presence of polarisation-dependent saturation of losses.

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