ISSN 0027-1349, Moscow University Physics Bulletin, 2010, Vol. 65, No. 3, pp. 174–179. © Allerton Press, Inc., 2010.
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# Optical Control of the Output Power of an Ytterbium Fiber Laser

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Received January 15, 2010; accepted February 1, 2010

**Abstract**—A new method of optical control of the output power of an ytterbium double-clad fiber laser is proposed. The method is based on the possibility of modulating the main channel gain coefficient inside an active element using the radiation of the competitive control channel. The advantage of this method consists in the fact that the main channel is modulated without inserting any controlling elements inside it. The static characteristics of the channel modulation are theoretically studied and the theoretical results are verified experimentally.

*Key words*: two-channel laser, ytterbium fiber laser, polarization, modulation, competition, power control.

**DOI:** 10.3103/S0027134910030045

## INTRODUCTION

Average- and high-power fiber lasers are of high practical interest, in particular for industrial applications [1–3], in medicine [4], for the pumping of fiber amplifiers [5–7], for studying nonlinear-optical phenomena in optical fibers, and as radiators for distributed sensors [8–12]. This explains the permanent interest in studying of their output characteristics [13–18]. Radiators with an output power controlled according to a given law, i.e., optical signal generators, are needed in various applications. Of a large number of fiber lasers types, ytterbium lasers have the highest efficiency factor and output power, which makes them the most promising ones for industrial applications [19, 20].

Thus, it is necessary to develop new and efficient means of the radiation modulation of average- and high-power ytterbium fiber lasers in the kilohertz modulation frequency range. In this work, the possibility of controlling the output power of the linear polarized radiation of the main channel of a double-clad ytterbium fiber laser by modulating losses in a competitive control channel, whose radiation is polarized perpendicular to the first channel, is proposed and experimentally confirmed.

The idea of using the competition of channels for modulation was proposed long ago in [21–23], in which the competition of two partially spatially separated channels with one general active element was considered. The experimental possibility of greatly increasing the modulation efficiency and, more importantly, avoiding the transition relaxation processes typical for solid-state lasers, was shown in [24, 25] for different types of two-channel lasers.

In this work, a scheme for the creation of a fiber laser with orthogonal polarizations in which the radiation of the main channel is modulated upon the modulation of losses in the control channel is proposed and theoretically studied.

## 1. THEORETICAL STUDY. IDEAL LASER

Figure 1a shows the idea of the proposed method; it shows the optical scheme of a laser with two orthogonal linearly polarized generation channels. An anisotropic active element *2* and a birefringent prism *3* are oriented so that their own polarization planes are colinear. Figure lb shows the optical scheme of the anisotropic laser used in the fiber performance.

To describe the laser with two polarized generation channels we use the simplest system of balance equations of the model of a two-channel four-level laser. This system can be obtained in a similar manner to that in equations (5.1) in [26] if a term responsible for cross-saturation of the modes is inserted or from [27] if the unnormalized variables $EN_i$, a part of the energy of the active medium accumulated in the volume of the $i$th channel, and $EF_i^{\text{in}}$, the in-resonator energy of photons of the $i$th channel, are used:

$$\frac{d(EN)_i}{dt} = K_i W_P - (EN)_i\left(\frac{1}{T_1} + \kappa_i (EF)_i^{\text{in}} + \kappa_j \xi_{ij} (EF)_j^{\text{in}}\right), \quad (1)$$

$$\frac{d(EF_i^{\text{in}})}{dt} = (EN)_i(\kappa_i (EF)_i^{\text{in}}) - \frac{(EF_i^{\text{in}})}{t_{Fi}}, \quad (2)$$

where $i = 1, 2$ is the channel number, $j = 3 - i$, $K_i$ is the efficiency factor of pumping of each channel, $W_p$ is the pumping power, $T_1$ is the relaxation time of the population of the upper laser level, $\kappa_i$ are the coefficients characterizing the efficiency of the interaction of photons of the corresponding generation channels with the active medium, $\xi_{ij}$ are the normalized coefficients of cross-saturation (CS) at $i \neq j$, the self-saturation coefficients are 1, and $t_{Fi}$ is the lifetime of photons of the $i$th channel. In the general case, the lifetimes of photons in the two channels differ.

Let us obtain explicit expressions for these times. To this end, we introduce the following notations: $R_{\mathrm{FBG}}$ is the reflection coefficient of the first mirror that is common for the main and control resonators, $R_1$ and $R_2$ are the reflection coefficients of mirror $M1$ (main resonator) and mirror $M2$ (control resonator), respectively, and $L$ is the resonator length (we consider it the same for two channels). Taking into account these notations, the lifetimes of photons in the main channel $t_{F_1} = -\dfrac{2Ln}{c\ln[R_1R_{\mathrm{FBG}}(1-\delta_1)^2]}$ and in the control channel $t_{F_2} = -\dfrac{2Ln}{c\ln[R_2R_{\mathrm{FBG}}(1-\delta_2)^2(1-\delta_{\mathrm{mod}})^2]}$, where $\delta_1$ and $\delta_2$ are the uncontrolled (parasitic) losses in the main and control channels, respectively, and $\delta_{\mathrm{mod}}$ are the controlled losses in a modulator.

Stationary solutions of the system of equations (1–2) can be obtained in an explicit form if the left-hand parts of equations are equalized to zero and the system is solved with respect to the energy of photons for both channels. Having done this, we obtain the expressions for the case of two-channel generation:

$$EF_1^{\mathrm{in}} = \frac{K_1W_pt_{F_1}\kappa_1 - \dfrac{1}{T_1} - \xi_{12}\left(K_2W_pt_{F_2}\kappa_2 - \dfrac{1}{T_1}\right)}{\kappa_1(1-\xi_{12}\xi_{21})}, \quad (3)$$

$$EF_2^{\mathrm{in}} = \frac{K_2W_pt_{F_2}\kappa_2 - \dfrac{1}{T_1} - \xi_{21}\left(K_1W_pt_{F_1}\kappa_1 - \dfrac{1}{T_1}\right)}{\kappa_2(1-\xi_{12}\xi_{21})}. \quad (4)$$

In the case of one-channel generation, when either the main or control channel is suppressed, stationary solutions of the system (1–2) are:

$$EF_1^{\mathrm{in}} = K_1W_pt_{F_1} - \frac{1}{\kappa_1T_1}, \quad EF_2^{\mathrm{in}} = 0; \quad (5)$$

$$EF_1^{\mathrm{in}} = 0, \quad EF_2^{\mathrm{in}} = K_2W_pt_{F_2} - \frac{1}{\kappa_2T_1}. \quad (6)$$

It is necessary to obtain the expressions of the output power from the solutions for the photon energy in the generation channels. In the first approximation the in-resonator energy of photons is related to the in-resonator power by the relationship $EF_i^{\mathrm{in}} = P_i^{\mathrm{in}}T_i^{\mathrm{tr}}$,

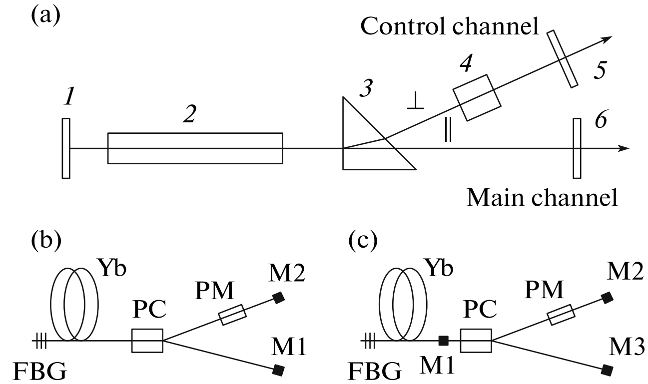


**Fig. 1.** (a) Principle laser scheme. Blank mirror *1* and translucent mirrors *5* and *6* form two Fabry–Perot resonators: for the control and main channels, respectively. The birefringent prism *3* is oriented so that the radiation of the main channel passed without refraction and the orthogonally polarized radiation of the control channel deviated from the optical axis and passed through the modulator *4*. (b) Design for the fiber performance: FBG, fiber Bragg grating; Yb, ytterbium laser; PC, polarization controller; PM, power modulator; Ml, mirror 1 M2, mirror 2. (c) Experimental model scheme. Unlike the previous case, the resonator of the control channel is formed by the Bragg grid and mirrors M1 and M2.

where $T_i^{\mathrm{tr}}$ is the time of the double passage of the resonator, and the output power: $P_i^{\mathrm{out}} = P_i^{\mathrm{in}}(1 - R_i)$. Then for the main channel:

$$P_1^{\mathrm{out}} = P_1^{\mathrm{in}}(1-R_1) = \frac{EF_1^{\mathrm{in}}}{T_1^{\mathrm{tr}}}(1-R_1) = EF_1^{\mathrm{in}}\frac{c(1-R_1)}{2nL},$$

and for the control channel:

$$P_2^{\mathrm{out}} = P_2^{\mathrm{in}}(1-R_2) = \frac{EF_2^{\mathrm{in}}}{T_2^{\mathrm{tr}}}(1-R_2) = EF_2^{\mathrm{in}}\frac{c(1-R_2)}{2nL}.$$

The transmission coefficient of the mirror Ml is chosen on the basis of the condition for obtaining the maximum output power of the main channel when the control channel is switched off. To find the optimum mirror, from the solution (5) one can get an algebraic equation whose root is the value of the reflection coefficient of the optimum mirror:

$$\frac{R_1-1}{\gamma_1^2R_1} - \frac{1}{\gamma_1} + B_1 = 0,$$

where $\gamma_1 \equiv \ln[R_1R_{\mathrm{FBG}}(1 - \delta_1)^2]$ and $B_1 \equiv \dfrac{c}{2nLT_1\kappa_1K_1W_p}$. The analytical solution of this equation is a very complicated problem. Therefore the equation roots are found numerically for each specific case.

We find the minimal possible reflection coefficient of the mirror M2 from the requirement of the full suppression of the radiation of the main channel when the control channel is opened, i.e., when the losses at the

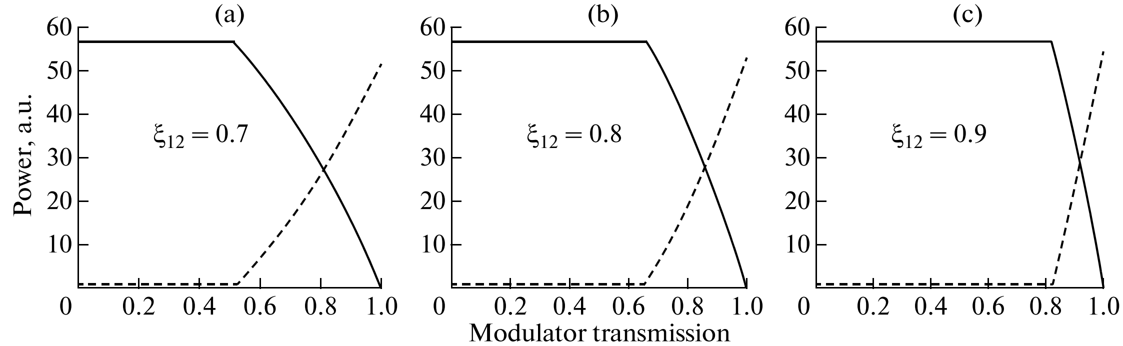


**Fig. 2.** Dependences of the power of the main (solid lines) and control (dotted line) generation channels on the transmission coefficient of the modulator for three values of the CS coefficients at the optimum output mirror $\xi_{12} = 0.7$ (a), $\xi_{12} = 0.8$ (b) and $\xi_{12} = 0.9$ (c).

modulator are zero ($\delta_{mod} = 0$). At the sought-for $R_2^{min}$ value the photon energy $EF_1^{in}$ the case of the two-channel generation is zero. Then if we insert $t_{F_1}$ and $t_{F_2}$ in solution (3) at given conditions and conduct simple algebraic manipulations, we can obtain the $R_2^{min}$ value:

$$R_2^{min} = \frac{1}{R_{FBG}(1-\delta_2)^2} \times \exp\left[-\frac{2nL}{c}\frac{\xi_{12}K_2W_p\kappa_2}{K_1W_p\kappa_1 t_{F_1} - \frac{1}{T_1}(1-\xi_{12})}\right]. \quad (7)$$

When the mirrors M1 and M2 are chosen optimally, the maximum efficiency and modulation depth of the output power of the main channel are achieved. Figure 2 shows the dependences of the output power of the channels on the modulator transmission at the optimal reflection values of the M1 and M2. It is seen that with an increase in the cross-saturation coefficient to 100% the modulation of the output power of the main channel requires a smaller range of the changes of the modulator transmission coefficient. For a cross-saturation coefficient of 0.9 a change of the transmission coefficient of the modulator of about 20% is required to obtain the 100% modulation depth of the main channel.

## 2. ANALYSIS OF A REAL LASER

To test this method experimentally, we designed the experimental model whose scheme is given in Fig. lc. In an experimental laser it is necessary to take into account the reflection from the butt end of the ytterbium fiber. To take this reflection into account, an additional mirror is incorporated in the laser model (mirror M1 in Fig. 1c). The radiation of the main and control channels is partially reflected from this mirror. The internal losses in the control channel are somewhat higher than those in the main channel; this provides the full suppression of the generation in the control channel in the absence of an additional external resonator, which is formed by the mirrors M2 and M3 (Fig. 1c) at the excess of pumping over the threshold less than $\alpha = 1.1$. In order to control the output power of the main channel, a modulator with the controllable transmission coefficient or a filter system with variable transmission was set up in the control channel.

To describe the performance of such a laser one can use the system of balance equations (1–2) by changing the expressions for the lifetimes of the photons in them. In such a complex resonator the radiation intensity of the main channel after the full passage (neglecting the time of the passage of the external part of the resonator is:

$$I_1(T_1^{pass}) \approx I_0R_{FBG}R_1(1-\delta_{11})^2 + I_0R_{FBG}R_3(1-R_1)^2(1-\delta_{11})^2(1-\delta_3)^2,$$

and that of the control channel is

$$I_2(T_2^{pass}) \approx I_0R_{FBG}R_1(1-\delta_{11})^2 + I_0R_{FBG}R_2(1-R_1)^2(1-\delta_{11})^2(1-\delta_2)^2(1-\delta_{mod})^2,$$

where $\delta_{11}$ and $\delta_{12}$ are the parasitic losses at the region from the Bragg mirror to the mirror Ml in the main and control channels, respectively, $\delta_2$ are parasitic losses in the external part of the resonator (from Ml to M2), $\delta_3$ those in the external part of the resonator (from Ml to M3), and $\delta_{mod}$ are controlled losses in the modulator. Then the lifetime of photons in the main channel is:

$$t_{F_1} = -\frac{2nL}{c\ln\{R_{FBG}(1-\delta_{11})^2[R_1 + R_3(1-R_1)^2(1-\delta_3)^2]\}},$$

and that in the control channel is

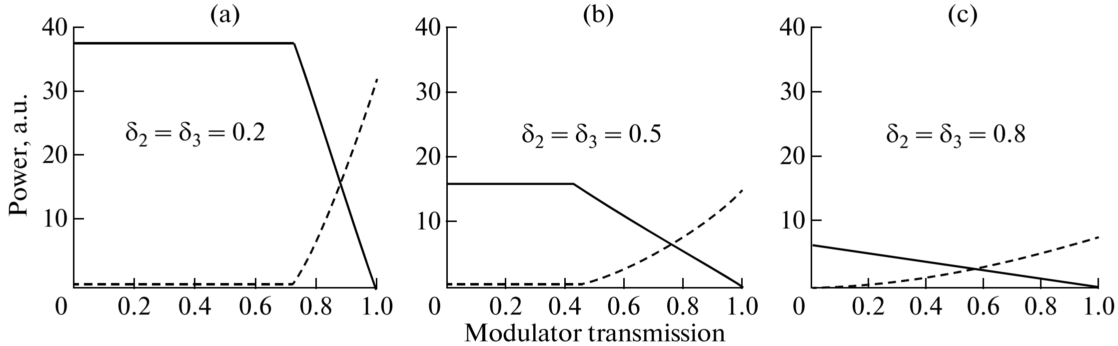


**Fig. 3.** Dependences of the power of the main (solid lines) and control (dotted line) generation channels on the modulator transmission coefficient for three values of the losses in the external part of the resonator at the optimum mirrors: $\delta_2 = \delta_3 = 0.2$ (a), $\delta_2 = \delta_3 = 0.5$ (b) and $\delta_2 = \delta_3 = 0.8$ (c).

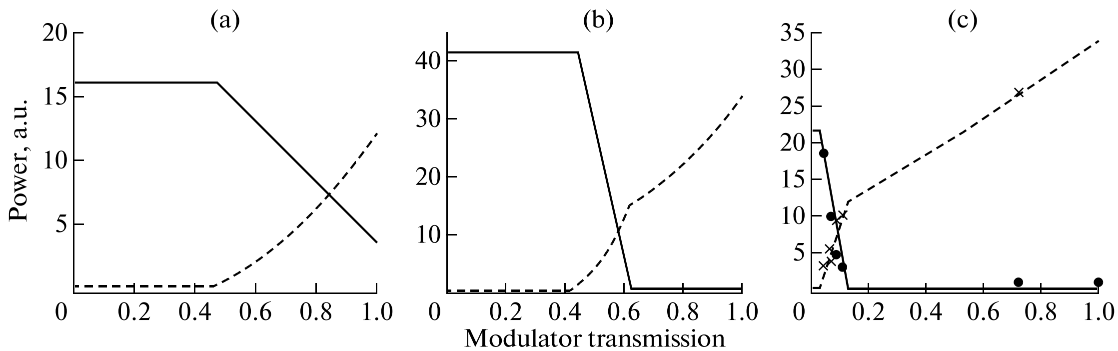


**Fig. 4.** Dependences of the power of the main (solid lines) and control (dotted line) generation channels on the modulator transmission coefficient with suboptimal mirrors: $R_2$ less than the optimum value (a), $R_2$ larger than the optimum value (b) and $R_2$ larger than the optimum value, $R_3 \approx 0$ (c).

$$t_{F_2} = -\frac{2nL}{c\ln\{R_{\mathrm{FBG}}(1-\delta_{12})^2[R_1 + R_2(1-R_1)^2(1-\delta_2)^2(1-\delta_{\mathrm{mod}})^2]\}}.$$

For the component resonator, the relationship of the output power and the in-resonator energy of photons changes as well. Taking into account the structure of the resonator, for the main channel one can obtain:

$$P_1^{\mathrm{out}} = EF_1^{\mathrm{in}}\frac{c}{2nL}(1-R_1)(1-\delta_3)(1-R_3),$$

and for the control channel

$$P_2^{\mathrm{out}} = EF_2^{\mathrm{in}}\frac{c}{2nL}(1-R_1)(1-\delta_2)(1-\delta_{\mathrm{mod}})(1-R_2).$$

In addition, the expressions for the optimum mirrors in the component resonator are changed. In the same manner as in section 2, we found numerically the value of the reflection of the optimum mirror M2. For the control channel the minimum value of the reflection of the mirror M2 is determined by the expression:

$$R_2^{\min} = \frac{\exp\left[-\frac{2nL}{c}\frac{\xi_{12}K_2W_p\kappa_2}{K_1W_p\kappa_1t_{F_1} - \frac{1}{T_1}(1-\xi_{12})}\right] - R_1R_{\mathrm{FBG}}(1-\delta_{12})^2}{R_{\mathrm{FBG}}(1-\delta_{12})^2(1-R_1)^2(1-\delta_2)^2}. \quad (8)$$

Figure 3 shows the graphs of the dependences of the output power of the channels on the modulator transmission for the setup used in the experiment. The dependences for three values of the losses in the external part of the resonator are shown in the case when mirrors M2 and M3 are optimally chosen. One can see that an increase in the $\delta_2$ and $\delta_3$ losses leads to a less steep dependence, i.e., to a decrease in the modulation efficiency. Unlike the case shown in Fig. 2, the increase in the losses reduces not only the modulation efficiency but also the maximum power of the main channel. Such losses can arise due to the insufficient quality of the alignment of mirrors M2 and M3.

In the case shown in Fig. 4, the mirror M2 was suboptimally chosen. Figure 4a shows a graph of the studied dependences, when $R_2$ is not high enough. This led to the modulation depth of the main channel failing to reach 100%. In Fig. 4b, on the contrary, $R_2$ exceeds the optimum value. One can see from this graph that the modulation efficiency of the main channel is rather high: only 20% of the losses are needed to completely suppress the generation of the main channel. It is, however, also necessary to create approximately 40% additional losses to reach the point at which the power of the main channel for the two-channel generation becomes zero.

Figure 4(c) shows the experimentally measured values of the power. One can see that the theoretical and experimental values coincide rather well and that the output mirrors were not chosen quite optimally: $R_3 \approx 0$, and $R_2$ in this experiment turned out to be too large (the generation of the main channel is suppressed at the modulator transmission of 0.12, rather than 1), i.e., to control the power of the main channel it is necessary to create greater losses in the modulator. It is important to note, however, that according to expressions (7) and (8) the optimal value of the reflection of the mirror M2 depends on the pumping power.

## CONCLUSIONS

In this work, a new method to control the output power of the linearly polarized radiation of the ytterbium fiber laser is proposed. It consists in the modulation of the gain coefficient of the main channel upon the modulation of losses in the control channel. The main advantage of this method is that in the main laser channel no additional elements are inserted and the modulator is placed in the control channel. Thus, the maximum efficiency factor of the laser is reached when the optimum mirror is used. The modulation depth can be of 100% at the strong competition between channels and low parasitic losses of the control channel.

The experimental results obtained in this work confirmed the possibility that one can control the power of the main channel of a ytterbium fiber laser by modulating the losses in the control channel. The theoretical and experimental results qualitatively coincide. For the complete quantitative coincidence of the experiment with theory, however, it is necessary to take into account the interaction of the channels in the absorbing region of the active fiber [28], as well as that fact that in each channel many longitudinal modes are generated [29]. Finding the conditions at which the model of the two-channel laser is applicable to the quantitative description of the dynamics of fiber lasers with two polarizations require additional analysis.


## ACKNOWLEDGEMENTS

The work is supported by the Leading Scientific School grant NSh-4408.2008.2 Experimental studies of the interaction of synchrotron and laser radiation with matter.


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