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CONTROL OF LASER RADIATION PARAMETERS

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A new approach to controlling the ytterbium fibre laser output power

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***Abstract*. A new approach has been proposed for controlling the linearly polarised output of an ytterbium-doped double-clad fibre laser: inverted-population modulation via loss modulation in a competing channel. The steady-state output power of the working channel has been determined as a function of loss in the competing channel. The results are qualitatively interpreted in terms of standard models of a dual-channel laser.**

Keywords: *dual-channel laser; fibre; fibre laser; polarisation; lasing threshold; modulation.*

1. Introduction

Medium- and high-power fibre lasers are of great practical interest, in particular for industrial [1 – 3] and medical [4] applications, for pumping fibre amplifiers [5 – 7], for probing the nonlinear optical response of optical fibres and as light sources for distributed sensors [8 – 12]. This accounts for the unabated interest in the study of their output characteristics [13 – 18]. Many applications require light sources with controlled variation in output power: optical signal generators. Among the many types of fibre lasers, the highest efficiency and output power are offered by ytterbium lasers, which thus hold the most promise for industrial applications [19, 20].

Direct laser output modulation via pump power modulation is limited to frequencies equal to the inverse of the excited-state lifetime: for ytterbium fibre lasers, $f_m = 1/T_1 \approx$ 1000 Hz ($T_1 = 10^{-3}$ s [21]). The generation of a modulated light output with the use of a low-power master laser producing pulses of the desired shape, which are then directed to external amplifiers, is limited to high-frequency modulation at frequencies above 100 kHz and is only possible when the average beam power is maintained constant. In the case of low-frequency modulation, transfer characteristics are highly nonlinear because of the saturation effect due to the inverted-population modulation in the amplifiers. In particular, telecommunications amplifiers exhibit transient effects, and special stabilisation systems are needed to combat such effects [22, 23]. Moreover, in the frequency range $1 < f_m < 100$ kHz, the laser output is difficult to modulate via loss modulation because of relaxation transients [24].

Thus, there is a real need for new, effective approaches to modulating the output of medium- and high-power ytterbium fibre lasers in the frequency range $1 < f_m <$ 100 kHz. Here, we examine and experimentally demonstrate the possibility of controlling the linearly polarised output of an ytterbium-doped double-clad fibre laser via loss modulation in a second, competing channel, with polarisation normal to that of the first channel.

The idea to utilise channel competition for modulation was proposed long ago by several groups [25 – 29], who considered the competition between two partly spatially separated channels sharing one active element. The possibility to substantially enhance the modulation efficiency and, more importantly, to eliminate relaxation transients, typical of solid-state lasers, was experimentally demonstrated for various types of dual-channel lasers [28, 29].

The coexistence of two linearly polarised coupled lasing channels in ytterbium-doped double-clad fibre lasers, established by Voronin et al. [14, 15], led them to examine the possibility of using the general concept of controlling the output power of one channel by modulating the loss in the other. Note that there is experimental evidence [17] that a neodymium fibre laser with two types of polarisations can be thought of according to its dynamic characteristics as a two-mode laser with two generalised polarisation modes.

In this paper, we present experimental evidence that the output power of the main channel of an ytterbium fibre laser can be controlled by modulating the loss in the competing lasing channel.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1. The active element (*4*) of the laser was a fibre consisting of a single-mode core, inner (silica) cladding and outer cladding, whose refractive index was lower than that of the inner cladding. The inner cladding had a square cross section: such geometry is optimal for achieving effective pump absorption in the core and reducing the pump loss at the fusion splice to a circular fibre [19]. The laser was pumped by a laser diode (*1*) with a multimode fibre pigtail (100-μm-diameter core, numerical aperture NA = 0.22). The pump power was up to 5 W at $\lambda = 0.98$ μm. The laser diode was protected from the fibre laser beam by a

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wavelength-selective filter (*2*) based on a double-clad fibre with a samarium-doped core [30]. This wavelength selector suppressed the fibre laser output in the range 1.03 – 1.30 μm by several orders of magnitude. The pump loss in it was within 0.5 dB, because the pump beam propagated mostly beyond the samarium-doped core. A fibre Bragg grating (*3*) was used as a highly reflecting mirror, and the other mirror was the fibre end (*5*), cleaved at 90°. The Bragg grating (*3*) [31] had a bandwidth of 0.7 nm and acted as a filter, restricting the laser linewidth. The reflectivity of the Bragg grating at 1081 nm was above 90 %.

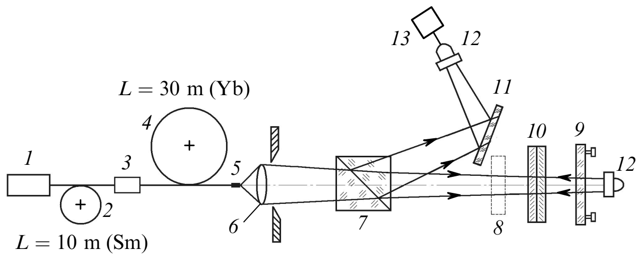

Figure 1. Schematic of the experimental setup: (*1*) laser diode; (*2*) samarium-doped fibre; (*3*) Bragg grating; (*4*) ytterbium-doped fibre; (*5*) fibre end face; (*6*) focusing lens; (*7*) polariser; (*8*) optical attenuator; (*9*) semi-transparent mirror; (*10*) filters; (*11*) mirror ($R = 100$ %); (*12*) photodiodes; (*13*) power meter.

At the output end of the fibre (*5*), the beam divergence was $\sim 14°$, so the beam was focused by a lens (*6*), which was placed so that the distance to the fibre end was slightly smaller than its focal length. Accordingly, the beam behind it was slightly convergent.

The laser beam was split into two polarised components by a birefringent polarising prism (*7*). The component polarised along the ordinary axis of the prism propagated with no deflection. After traversing an optical attenuator (*8*), semi-transparent mirror (*9*) and optical filters (*10*), it entered a photodiode (*12*). The extraordinary wave was deflected by an angle, reflected from a mirror (*11*) and entered a power meter (*13*). The semi-transparent mirror (*9*) redirected part of the beam to the laser cavity, forming an additional cavity, or a feedback loop, for the polarisation component that formed the control channel of the laser. The working (main) laser cavity, corresponding to an orthogonal polarisation, was formed by the fibre Bragg grating and the end face of the active fibre. The attenuator (*8*) was used to adjust the additional cavity, and was then removed from the beam path. The optical filters (*10*) were used to produce extra losses in the central-beam circuit.

The signals from the photodiodes (*12*) were fed to a spectrum analyser and an ACK-3151 two-channel digital oscilloscope and were stored on a computer.

3. Experimental results

Our experimental data show that the dynamics of the ytterbium fibre laser output depend significantly on the pump power, active fibre length and temperature.

At pump powers slightly above threshold ($\alpha = 1 - 1.2$), we observe lasing spikes (Fig. 2a). Their repetition frequency in the lower loss channel markedly exceeds that in the orthogonal polarisation channel. In the range $\alpha =$

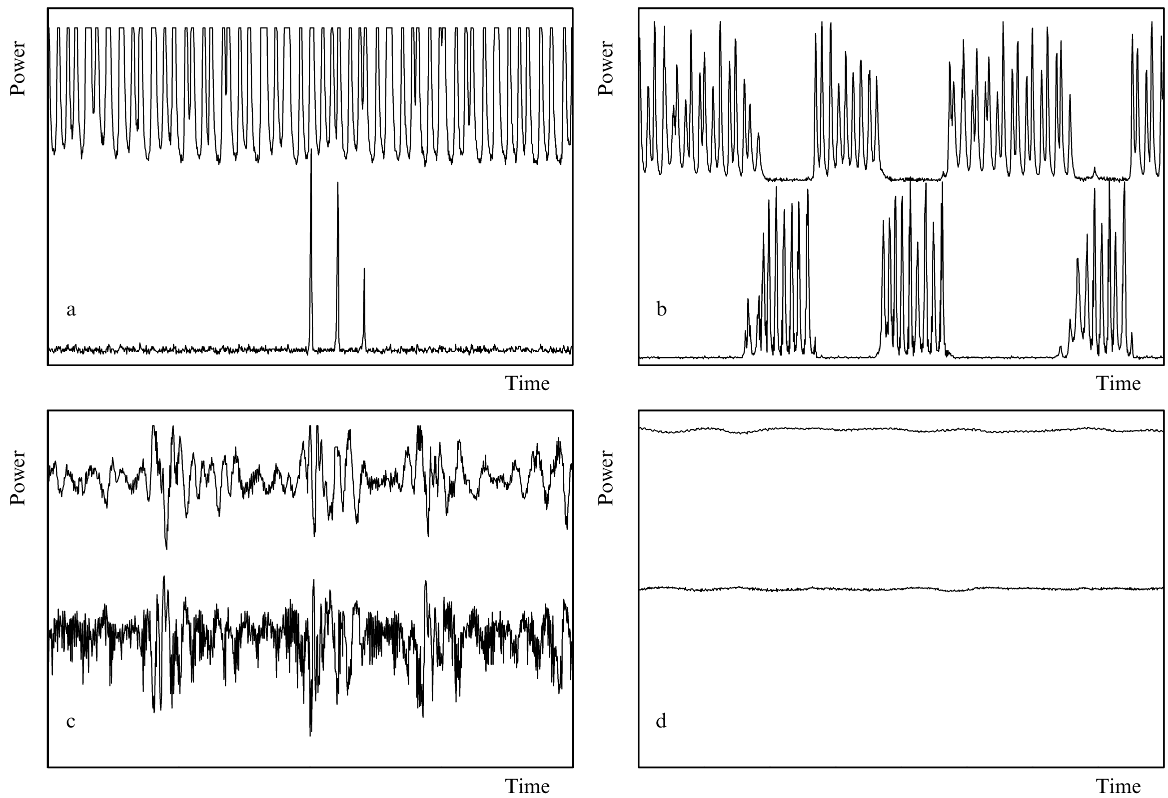

Figure 2. Time dependences of the output power for two orthogonally polarised lasing channels at four pump power levels: $\alpha = 1.15$ (a), 1.19 (b), 1.47 (c), and 1.9 (d). Time base, 0.5 ms div^{-1}. The upper and lower traces represent the control and main channels, respectively.

1.2 – 1.45, spontaneous polarisation switching occurs [15] (Fig. 2b), causing the average power in the two orthogonally polarised channels to periodically vary from a maximum level to nearly zero. Figure 3 plots the measured switching frequency against pump power. Note that, in addition to the relatively slow, medium-power switchings between the two channels, there is amplitude spike modulation, whose frequency increases with pump power. At higher powers, we observe steady-sate lasing in the two polarisation channels (Figs 2c, 2d).

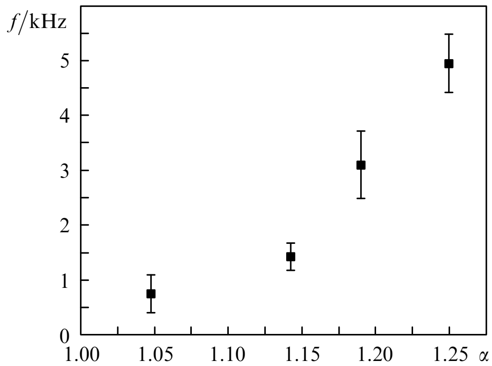

Figure 3. Lasing switching frequency as a function of pump parameter.

Our experimental results demonstrate that the loss in the external part of the control channel cavity has a significant effect on the output power and lasing dynamics of the main channel. Varying the transmission of the neutral filters, one can control, e.g., the switching frequency and pulse repetition time in the main lasing channel in the spontaneous switching regime (Fig. 2b).

Figure 4 shows steady-state dependences of the main-channel output power on the (double-pass) transmission of additional neutral filters in the external part of the control channel cavity at two pump powers corresponding to steady-state dual-channel lasing (Figs 2c, 2d). From the viewpoint of practical application, channel power control

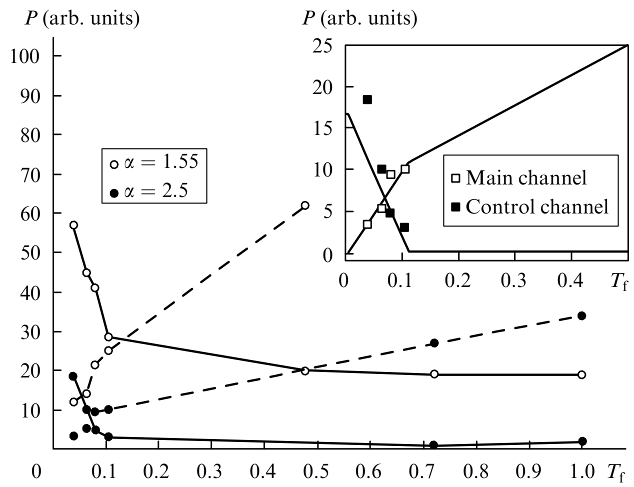

Figure 4. Output powers of the main (dashed lines) and control (solid lines) lasing channels vs. transmission T_f of additional filters in the external part of the cavity at $\alpha = 1.55$ and 2.5. Inset: theoretical dependences (solid lines) and data points at $\alpha = 1.55$.

is of interest under such, quasi-steady-state lasing conditions.

It is also seen from Fig. 4 that at $\alpha = 2.5$ the slope of the main-channel output power as a function of the transmission of the neutral filter in the control channel is lower than that at $\alpha = 1.55$. Consequently, the output power modulation efficiency, defined as the ratio of the difference between two laser output powers to the difference between the corresponding transmittances of filters (*10*), decreases with increasing pump power. Of key importance, however, is that the output power of the main channel can be controlled without additional losses in it even at pump powers well above threshold.

4. Discussion

The present experimental data, confirming that the output power of the working channel of an ytterbium fibre laser can be controlled via loss modulation in the control channel, can be understood in terms of the simplest model of a dual-channel laser [17, 32]. At the same time, to interpret the spike and switching regimes (Figs 2a, 2b), coupling of the channels in the absorbing region of the active fibre must be taken into account [33].

The physical mechanism of output power modulation in the two channels of a dual-channel laser when the loss is modulated in only one of them was clarified earlier by Nanii [32], who analysed a system of phenomenological equations that took into account the competitive interaction between the lasing channels in the active medium. The applicability of a dual-channel laser model to the polarisation dynamics in a neodymium-doped fibre laser with two polarisations was shown even earlier [17].

Unfortunately, the dual-channel lasing approximation fails to provide quantitative agreement between theory and experiment. One reason for this is that the control channel has a compound cavity: the end face of the active fibre and the semi-transparent mirror (*9*) form an extra cavity, which has a significant effect on the mode composition of the radiation in the control channel. In our experiments, the mode structure is influenced by the transmission of the optical filters (*10*) in the external cavity. Moreover, the presence of coupled cavities in the control channel substantially increases the mode spacing in this channel. To reach quantitative agreement between theory and experiment, the mode structure of the working and control channels should be taken into account, which would inevitably increase the number of coupled equations and add complexity to theoretical analysis.

On the other hand, both in experiment and in practical application of the proposed approach to modulating the output power of the working channel, it is desirable to eliminate reflection from the fibre end in the control channel. This would enhance the modulation efficiency and stabilise the laser output.

In a theoretical model of a dual-channel laser [17, 32], cross-saturation coefficients are independent of pump power. There is, however, experimental evidence that they may vary with pump power [34]. One possible reason for this is the highly nonuniform longitudinal pump power distribution. Since the ytterbium fibre laser is a quasi-three-level system, at pump powers slightly above threshold there is an absorption region in the active fibre, which has a significant effect on lasing dynamics. With increasing pump power, the cavity becomes more transparent and the radiation penetrates deeper, changing the inverted-population distribution, which may lead to changes in cross-saturation coefficients.

5. Conclusions

A new approach has been proposed for controlling the linearly polarised output of an ytterbium fibre laser: loss modulation in a control channel. Its main advantage is that the modulator is located in the control channel, with no additional elements in the working channel. The steady-state output power of the lasing channels has been measured as a function of loss in the control channel. Analysis of the data demonstrates that the proposed approach enables effective control of the ytterbium fibre laser output power.

The principle of controlling the output power of the working channel by modulating the loss in a control channel can be interpreted in terms of a phenomenological model of a dual-channel solid-state laser, which takes into account channel competition in the gain medium. However, given that the control channel has a compound cavity, changes in its mode composition must be taken into account, which makes the simplified dual-channel model unsuitable for a quantitative comparison of experimental data with theoretical predictions. Most likely, quantitative agreement between theory and experiment will be reached when the multimode structure of the radiation in both channels will be taken into account.

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