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Tunable laser Ti:Al_2O_3 with the SBS cell

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Results of investigations on a self-injection locked, passively switched Ti:sapphire laser are presented. Shortening and stabilization of pulse duration have been achieved using the SBS cell inside of the laser cavity. The main advantages of this laser and its features are shown.

1. Introduction

The progress in the field of technology of crystals doped with metal ions which took place in the 70s and 80s caused the appearance of a series of new crystalline, active materials characterized by wide luminescence bands and thus suitable for the tunable lasers. Such crystals as alexandrite ($BeAl_2O_3:Cr^{3+}$), sapphire doped titanium ($Al_2O_3:Ti^{3+}$), forsterite ($Mg_2SiO_4:Cr^{4+}$) and the so-called black YAG ($Y_3Al_5O_{12}:Cr^{4+}$) enable the construction of tunable lasers operating at room temperature in the range from 700 nm to 1580 nm [1].

A very important parameter of tunable lasers is the width of a generation line. The narrowing of the laser generation spectra which are expected to generate the mono-pulses with the high energy faces the following difficulties: losses in the laser resonator caused by the elements with high dispersion result in a decrease of generation efficiency, a low threshold of damage to diffraction grating surfaces and interferometers F-P makes it impossble to apply them in the lasers operating with the high threshold exceeding. Moreover, the energetic pulse parameters (energy, peak power and pulse duration) get worse with the offset of generation wavelength from the centre of a luminescence line [2].

The methods eliminating the above disadvantages are well known [3]. The solution is an application of a laser with self-injection. In the resonator of this laser one distinguishes two branches: dispersive and non-dispersive. In the common part of both branches there is the laser medium. The dispersive branch operates only during the linear development of a generation and the non-dispersive branch is switched on when the radiation begins to increase in an avalanche way. In the laser with self-injection it is necessary to switch over the resonator from the dispersive branch to the non-dispersive one. A self-injection laser can be passively or actively switched. With the active control of the resonators switching, during the generation, the essential problem is to have complex, precise, reliable and very fast switching systems.

In the present paper we suggest to use the SBS phenomenon in the dispersive resonator of the mono-pulse tunable laser Ti:Al_2O_3 for the automatic switching over of the resonator from the dispersive branch to the non-dispersive one.

2. Experimental set-up

The scheme of an optical system of the tunable laser with the SBS cell is shown in Fig. 1. The dispersive branch of the tunable laser presented consists of the holographic diffractive grating HG (30 × 10 mm, 3600 lines/mm, efficiency of 80% in the range of $\lambda = 700-900$ nm), prismatic telescope P (glass BK7). The measured width of a generation line of the laser is $\delta\lambda \approx 17$ pm. The remaining optical elements of the laser are:

1. Output mirror M_{out} – double-plate selector with the energetic reflection coefficient $R = 45\%$.

2. Active medium – Ti:Al_2O_3 crystal of 20 mm in length with the cut faces at the Brewster angle, concentration $N_a = 2.5 \times 10^{19}$ cm^{-3} (0.1% by weight), absorption coefficient for $\lambda = 532$ nm, $\alpha = 1.75$ cm^{-1}, figure of merit $\mathrm{FOM} = \dfrac{\alpha(490\ \mathrm{nm})}{\alpha(800\ \mathrm{nm})} = 35$, energetic threshold of damage about 400 MW/cm^2.

3. Lens telescope $L_1 - L_2$ – lenses with the 50 mm focal length without the anti-reflexive layers, applied in order to increase the intensity of radiation in a cuvette filled with acetone, as well as to increase the SBS efficiency.

4. Cuvette M_{SBS} filled with acetone, which is closed on both sides by the plane-parallel plates without antireflexive layers, length – 70 mm, diameter – 10 mm.

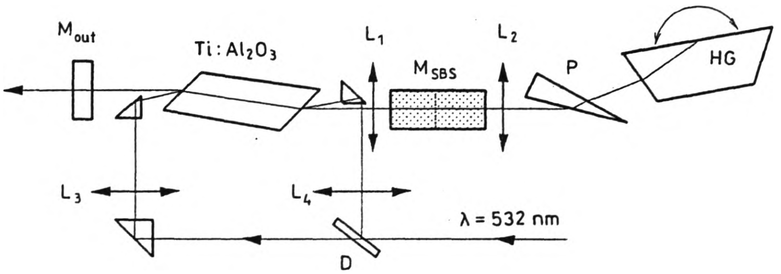

Fig. 1. Optical scheme of the titanium laser with the SBS cell in a configuration of the resonator with the diffractive grating HG (P – prismatic telescope, D – energy divider, $R = 0.5$, $T = 0.5$, $\lambda = 0.53$ μm)

The titanium laser has been pumped by the second harmonic of Nd:YAG laser with the Q modulation by means of the Pockels cell (pulse duration $\tau_p = 8$ ns, pulse energy $E_{in} = 45$ mJ). In order to achieve homogeneity of the cross-section of the pumping channel there was applied the double-side pumping of the Ti:Al_2O_3. Moreover, in this way there was obtained a double decrease of the intensity of pumping radiation at the Ti:Al_2O_3 crystal surface. The resonator length of Ti:Al_2O_3 laser was 50 cm.

3. Theoretical description

The SBS mirror divides the resonator of the titanium laser (Fig. 1) into two parts: non-dispersive (output mirror M_{out}, active medium, SBS mirror M_{SBS}) and dispersive part (SBS mirror, dispersive elements HG, P). The energetic reflection coefficient SBS (R_{SBS}) depends on the intensity of radiation incident on the cuvette with the dispersive medium:

– for

$$[W_0/W_1]^2 I^+(z_0,t) < I_p, \quad R_{SBS} = 0, \tag{1a}$$

– for

$$[W_0/W_1]^2 I^+(z_0,t) \geqslant I_p, \quad R_{SBS} = 1 - \frac{I_p}{[W_0/W_1]^2 I^+(z_0,t)} \tag{1b}$$

where: $2W_0$ – diameter of the cross-section of a laser beam in the resonator at the L_1 lens of the $(L_1 - L_2)$ telescope,

$2W_1$ – diameter of the cross-section of a laser beam in the focus of the $(L_1 - L_2)$ telescope,

$I^+(z_0,t)$ – power density of the beam incident on the M_{SBS} mirror (W/cm^2],

I_p – value of the threshold power density SBS [W/cm^2],

z_0 – coordinate of the telescope $(L_1 - L_2)$ focus.

The (W_0/W_1) ratio describes the multiplication factor of the increase of power density of radiation incident on the SBS cuvette in the focus of the $(L_1 - L_2)$ telescope. From relationship (1) it results that the generation process of the tunable laser with the SBS cell can be divided into two stages:

1. The linear generation development which lasts until the moment when the density of power radiation in the resonator exceeds the threshold density SBS (I_p). At this stage, the generation spectrum is created.

2. The avalanche development of generation – exceeding the threshold power density causes the reverse reflection of radiation from the SBS mirror with high efficiency and thus immediate switching off of the losses introduced to the resonator by the dispersive elements (switching off of the dispersive branch) and the shortening of the resonator. At this stage, there are created the energetic-time characteristics of a generated mono-pulse. The SBS mirror protects the dispersive elements against the damage by laser radiation.

For the analysis of the process of mono-pulse generation of Ti:Al_2O_3 laser with the SBS cell there were used the equations of energy transport, which take into account the changes of amplification coefficient and the changes of density of photons stream in time and space. These equations are as follows:

$$\frac{\partial I_\lambda^+(z,t)}{\partial z} + \frac{1}{V_\lambda}\frac{\partial I_\lambda^+(z,t)}{\partial t} = [k_\lambda(z,t) - \rho_m] I_\lambda^+(z,t), \tag{2a}$$

$$-\frac{\partial I_\lambda^-(z,t)}{\partial z} + \frac{1}{V_\lambda}\frac{\partial I_\lambda^-(z,t)}{\partial t} = [k_\lambda(z,t) - \rho_m] I_\lambda^-(z,t), \tag{2b}$$

$$\frac{\partial k_\lambda(z,t)}{\partial t} = -\frac{[I_\lambda^+(z,t)+I_\lambda^-(z,t)]k_\lambda(z,t)}{E_s} - \frac{k_\lambda(z,t)}{\tau} \tag{2c}$$

where: I_λ^+, I_λ^- – power densities of the beam propagating in a resonator, accordingly – in the "+" direction and "−" direction of the optical axis of the resonator [W/cm^2],

ρ_m – material losses of the active medium [cm^{-1}],

k_λ – gain coefficient [cm^{-1}],

τ – emission lifetime,

$V_\lambda = c/n_\lambda$ – velocity of propagation in the active medium (c – in air),

n_λ – refraction coefficient of the active medium,

$(L_1 - L_2)$ – telescope,

$E_s = h\nu/\sigma(\nu)$ – saturation energy,

h – Planck constant,

ν – frequency of generated radiation,

$\sigma(\nu)$ – emission cross-section.

Index λ in the above equations denotes that these equations are valid for the generation wavelength λ, therefore λ is a parameter. It results from this fact that in order to obtain the pulse characteristic as a function of wavelength of tunable laser generation, it is necessary, in case of λ changes, to solve the system of equations each time. These equations are useful for the analysis of dynamics of phenomena occurring in lasers.

Equations (2) have been solved using the initial conditions for the power densities of the beam I^+, I^- and for gain coefficient $k(\lambda)$ as well as using the initial conditions at the output SBS mirror (taking into consideration the relationship (1)) and at the substitute tunable mirror the reflectivity of which regarded the losses of dispersive branch of a resonator. The initial and boundary conditions regarded the real parameter values of the resonator, which is presented in Fig. 1.

4. Experimental investigations

In the following figures, there are shown the characteristics of an energy generation and a pulse duration of generation as a function of wavelength λ. The continuous curves were obtained on the basis of numerical analysis of Eq. (2), whereas the experimental values are denoted as squares for the Ti:Al$_2$O$_3$ laser with the SBS cell and as triangles for the Ti:Al$_2$O$_3$ laser with the classical resonator (without the SBS cell).

The pulse duration as a function of generation wavelength is shown in Fig. 2. This figure univocally shows that the application of SBS cell enables the shortening of a generation pulse duration. One of the reasons for these changes is an effective shortening of resonator length occurring at the moment of switching on of the SBS mirror. Simultaneously, there follows a decrease in resonator losses for losses of the switched-off branch. Since the total resonator losses of titanium laser with the diffraction grating amount to $\rho = 0.491$ cm^{-1}, the switching off of rather great losses

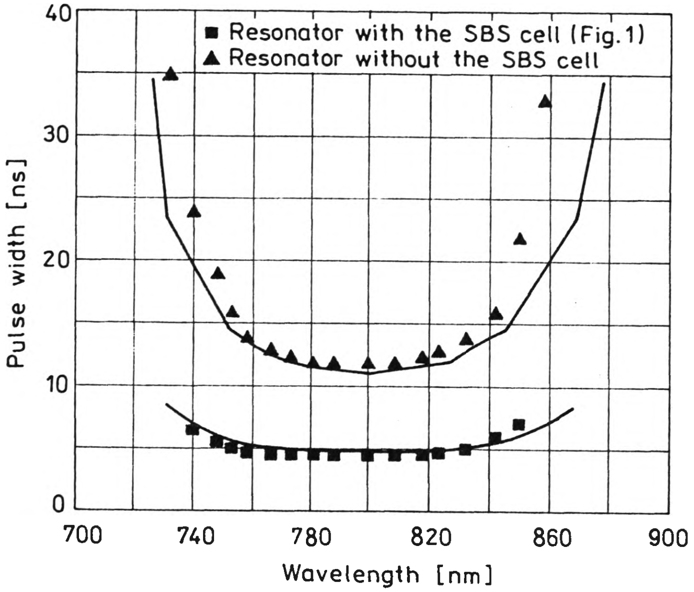

Fig. 2. Pulse duration dependence on Ti:Al_2O_3 laser generated wavelength

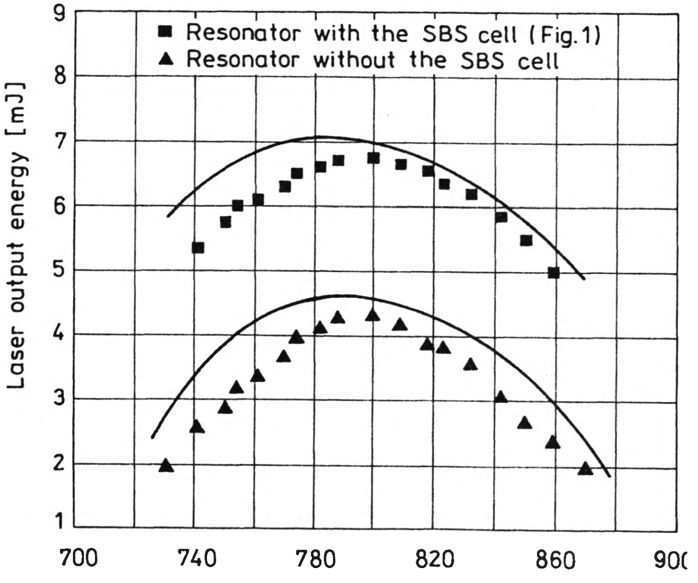

Fig. 3. Ti:Al_2O_3 laser output energy *vs.* generated wavelength

of the dispersive branch $\rho_d = 0.127$ cm^{-1} as well as half of the SBS mirror losses and the telescope $(L_1 - L_2)$ losses $\rho_{SBS} = 0.124$ cm^{-1} before the start of the avalanche development of generation should significantly influence the increase of energy of pulse generation. This fact is confirmed by the energetic characteristics of a generation of the lasers with SBS cell as well as with the classical resonator, as a function of a generation wavelength. These characteristics are presented in Fig. 3. They univocally show that using the SBS cell in resonator of the tunable laser, the energies of generated mono-pulses can increase. Application of the SBS cell in the titanium laser with the diffractive grating has caused 2.5 times increase of generation energy for extreme wavelengths of tunable characteristic and 1.7 times increase of energy in the maximum of this characteristic. Due to this fact one can see that SBS mirror additionally stabilizes the generation energies. For a laser with the classical resonator the process of tuning the generation wavelength from the short-wave limit of tunable band to the maximum of the tunable characteristic is accompanied by the change of generation energy from 2 mJ to 4.3 mJ (2.1 times increase). In the laser with the SBS cell the above change of generation wavelength is accompanied by the change of generation energy from 5.4 mJ to 6.7 mJ (1.2 times increase).

The increase of generation energy, in the case of applying the SBS cell, results from the fact that almost all energy, accumulated in the active material, is released in a generation pulse which is formed in the resonator with the excluded dispersive branch, that is, in a resonator which has smaller useless losses in comparison with the output resonator. This part of energy, cumulated in the active medium which was lost in the dispersive branch remains in the laser with the SBS cell, and it can be generated in the generation pulse. Of course, not all energy was generated, because first – a part of this energy is dispersed as a result of the Fresnel's losses appearing in the optical elements of SBS cell as well as due to absorption process in the dispersive medium. The second reason of the energy dispersion is the fact that the dispersive branch is not excluded in 100%. The increase of mono-pulse energy of the laser with the SBS cell results also from the fact that switching off of the dispersive branch, before the pulse generation, causes an increase of the initial threshold exceeding and thus more effective use of the energy which is cumulated in the active medium, because the final amplification coefficient is the smaller the higher an initial threshold exceeding is.

The beam profile generated by $Ti:Al_2O_3$ laser with SBS cell was Gaussian, however, the divergence of radiation was insignificantly greater ($\Theta \approx 1$ mrad) than the divergence of laser with the classical resonator ($\Theta \approx 0.8$ mrad).

5. Conclusions

On the basis of the results obtained from the theoretical analysis as well as from the experimental investigations, the following conclusions can be drawn:

1. The SBS cell placed in the resonator of the dispersive laser in an effective way switched off the losses of the dispersive branch of a resonator before the start of the avalanche stage of a generation development. Switching off of losses and the shortening of a resonator, during the generation, causes next that the generated mono-pulses are characterized, in comparison with the mono-pulses generated by the laser with the classical resonator, by:

a) higher energy in the whole tunable range,

b) shorter duration in the whole tunable range,

c) higher peak power in the whole tunable range.

2. The SBS cell stabilizes the duration of pulse generation and the energies of generated mono-pulses. That means that offset of the generation wavelength from the maximum of tunable characteristic $\lambda = 800$ nm does not cause such great changes of the above parameters as it is for the tunable laser with the classical resonator.

3. An application of the SBS cell is especially useful in the tunable lasers with the resonator of high dispersion. The experimental investigations carried out on the titanium laser with the branch with significantly lower dispersion ($\delta\lambda \approx 0.3$ nm) gave worse results.

References

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