Секция 3. ФИЗИЧЕСКИЕ, ФИЗИКО-МАТЕМАТИЧЕСКИЕ, МАТЕРИАЛОВЕДЧЕСКИЕ И ТЕХНОЛОГИЧЕСКИЕ ОСНОВЫ ПРИБОРОСТРОЕНИЯ

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DIODE-PUMPED Er,Yb:GdAB LASER PASSIVELY Q-SWITCHED BY MBE-GROWN Cr:ZnS/Cr,Co:ZnS THIN FILMS

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Q-switched erbium lasers emitting in the 1.5-1.6 µm spectral region are widely used in optical location and LIBS (Laser Induced Breakdown Spectroscopy) systems because of eye-safety and weak absorption in the atmosphere. Er,Yb:$GdAl_3(BO_3)_4$ (Er,Yb:GdAB) crystal was shown to be an efficient laser material for the 1.5-1.6 µm spectral range [1]. A passively Q-switched regime of operation of Er,Yb:GdAB laser was demonstrated recently with Co^{2+}:$MgAl_2O_4$ crystal as saturable absorber [2]. Here we report a diode-pumped Er,Yb:GdAB laser emitting near 1.5 µm passively Q-switched by using of MBE-grown Cr:ZnS and Co,Cr:ZnS thin films.

Thin films of Cr-doped ZnS were deposited using the high purity materials (99.999% purity) in the UHV MBE deposition system at base pressure of ~4×10^{-9} Torr and thermal evaporation [3]. High-quality polycrystalline films transparent through the visible and infrared regions were obtained with absorption peak at 1600 nm indicating dominance of the Cr^{2+} oxidation state and a fluorescence peak at 2000 nm. Film thickness was kept in the range 2 to 8 µm with Cr content varied from 0.01 to 3 at.%. Cobalt was added as a codopant to some of the films at 0.1 at.% content.

Absorption and fluorescence spectra of Cr-single-doped films show a well-defined Cr^{2+} bands centered at 1.7 µm and 2 µm, respectively, related to the transitions between ^5E and $^5T_2$ energy levels (Fig. 1a, 1b). Fabry-Perot etalon effect in the thin Cr:ZnS film resulted in spectrum modulations for both absorption and emission spectra. Swanepoel analysis [4] was used to eliminate the modulations from the absorption spectra. The $^5T_2$ level lifetime was found to be concentration dependent, decreasing from 5.4 µs for 0.012 at.% doped film to 1.3 µs for 0.1 at.% doped film [5].

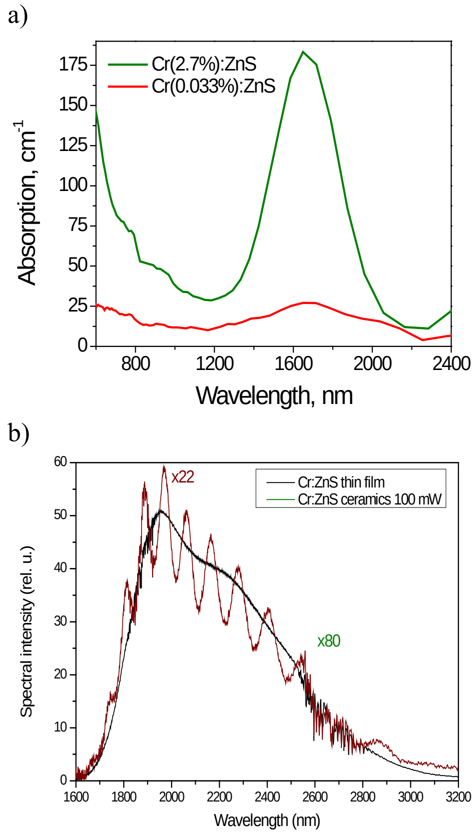

Fig. 1. The absorption (a) and fluorescence (b) spectra of the Cr:ZnS thin films and single crystal

The high quality Er,Yb:GdAB crystal was grown by dipping seeded high-temperature solution growth. The concentrations of the dopants were measured to be 1 at.% for Er^{3+} and 11 at.% for Yb^{3+}. The laser cavity consisted of pump mirror (PM) (R>99.5% at 1522 nm and T>95% at 976 nm) deposited onto external side of the crystal and a flat output coupler (OC) with transmission of 9% at 1522 nm. A saturable absorber (SA) – few-µm thick Cr:ZnS film on 1-mm-thick sapphire substrate - was inserted between the laser element and OC. The minimal geometrical cavity length was about 4 mm, that was limited by the design of the active element cooling system. The active element (AE), a 1-mm-thick, c–cut Er,Yb:GdAB crystal was wrapped in indium foil and mounted between two copper slabs with a hole in the center to permit passing of pump and laser beams. Its temperature was kept at 14 °C by means of thermo-electrical cooling elements with water-cooled heatsink. A 976 nm fiber-coupled (Ø105 µm, NA=0.22) laser diode emitting unpolarized radiation at 976 was used as a pump source. The pump beam was focused into the crystal by a focusing system into 120 µm spot ($1/e^2$ intensity). The small-signal pump absorption of the crystal was measured to be near 75%. The setup for laser experiments is schematically shown in Fig. 2.

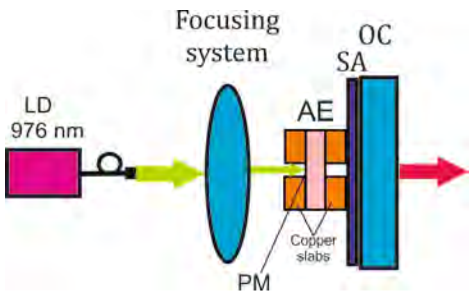

Fig. 2 Schematics for laser experiment

Stable passively Q-switched regime of the Er,Yb:GdAB laser was obtained with Cr:ZnS thin films having Cr concentration from 0.1 to 0.5 at. %. The best laser performance was achieved for 5-µm-thick 0.1 at.%-doped film additionally codoped with 0.1 at.% Co, having initial Fresnel-free transmission about 4%. The maximum average output power of 332 mW was demonstrated at 1522 nm (Fig. 3). The spatial profile of the output beam was TEM_{00} mode with M^2 parameter less than 1.5 (see inset in Fig. 3).

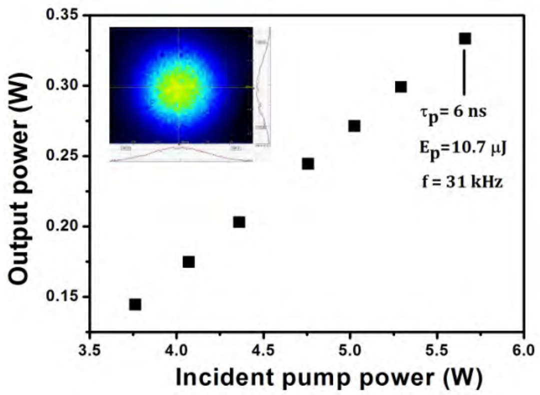

Fig. 3. Average output power vs. absorbed pump power of Q-switched Er,Yb:GdAB laser. The inset shows output beam profile

Laser pulses with energy of 10.7 µJ and duration of 6 ns were obtained at a repetition rate of 31 kHz when the incident pump power was about 4.5 W. The oscilloscope trace of the shortest single Q-switched pulse measured at incident pump power of 4.5 W with corresponding pulse train is presented in Fig. 4.

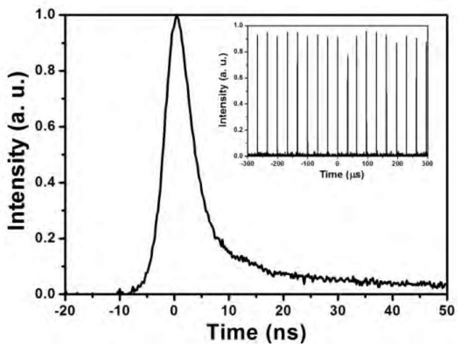

Fig. 4. Oscilloscope traces of the shortest pulse and the corresponding pulse train

In conclusion, passively Q-switched Er,Yb:GdAB laser with MBE-grown Cr:ZnS/Cr,Co:ZnS thin film saturable absorber was demonstrated for the first time to our knowledge. The pulses with 10.7 µJ energy, 6 ns duration, and 31 kHz repetition rate were obtained at the wavelength of 1522 nm. The saturable absorber manufacturing technique allows obtaining integrated AE-SA structures especially interesting for compact microchip Q-switched lasers with minimal pulse duration.

1. K.N. Gorbachenya, V.E. Kisel, A.S. Yasukevich, V.V. Maltsev, N.I. Leonyuk, and N.V. Kuleshov, "Highly efficient continuous-wave diode-pumped $Er,Yb:GdAl_3(BO_3)_4$ laser," Opt. Lett. **38**, 2446–2448 (2013).
2. K.N. Gorbachenya, V.E. Kisel, A.S. Yasukevich, V.V. Maltsev, N.I. Leonyuk, and N.V. Kuleshov, "Eye-safe 1.55 µm passively Q-switched $Er,Yb:GdAl_3(BO_3)_4$ diode-pumped laser," Opt. Lett. **41**, 918–921 (2016).
3. E. Karhu, N. Tolstik, E. Sorokin, S. Polyakov, R. Zamiri, V. Furtula, U. Osterberg, I.T. Sorokina, and U. J. Gibson, "Towards Mid-IR Waveguide Lasers: Transition Metal Doped ZnS Thin Films," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (2016) (Optical Society of America, 2016), paper STu4R.2.
4. R. Swanepoel, "Determination of the Thickness and Optical-Constants of Amorphous-Silicon," J. Phys. E-Sci. Instrum. 16, 1214–1222 (1983)
5. N. Tolstik, E. Sorokin, E. Karhu, S. Polyakov, U. Gibson, and I.T. Sorokina, "MBE-grown Cr:ZnS Thin Film Laser Media," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (online) (Optical Society of America, 2016), paper JF1K.5.