Highly efficient, narrow-linewidth, and single-frequency actively and passively Q-switched fiber-bulk hybrid Er:YAG lasers operating at 1645 nm

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Abstract: High power, highly efficient single frequency oscillation of Er:YAG fiber-bulk hybrid laser at 1645 nm is demonstrated in actively and passively Q-switched operation modes. The slope efficiencies in the active and passive Q-switched operation reached 75% and 20%, respectively, with the record output powers in the narrow-linewidth and single longitudinal mode regimes of operation.

OCIS codes: (140.3580) Lasers, solid-state; (140.3070) Infrared and far-infrared lasers; (140.5680) Rare-earth and transition-metal solid-state lasers

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1. Introduction

Eye-safe laser sources operating at 1.5-2.0 μm are widely used in commercial and scientific applications. Commercially available high power Erbium and Thulium doped fiber lasers are the lasers of choice when continuous wave radiation is required. Recent progress with high repetition rate (1-10 kHz), high peak power, high pulse energy, narrow linewidth (single frequency) laser sources is mainly associated with the novel fiber-bulk hybrid system concept. In this approach, highly efficient, high power, and high brightness fiber lasers are used for “quasi-resonance” pumping of a bulk solid state laser media. Resonance pumping facilitates lasing with a small quantum defect, simplifies thermal management, and enables power scaling capabilities. For example, Stokes shift could be less than 6% in the case of fiber pumped Er:YAG hybrid laser [1-5]. This approach also combines high efficiencies and high-power operation of fiber lasers with the high energy-storage capabilities of bulk lasers. The

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slope efficiency of the Er:YAG hybrid laser with respect to incident pump power was reported to be 80.7% in the CW operation mode [1]. Slope efficiency in the Q-switched operation mode 62% at 10 kHz repetition rate was described in [4]. Additional challenge arises when one would like to control oscillation wavelength. In this case utilization of intracavity selective elements causes decrease of laser efficiency. In the paper [5] the authors used a 300 μm thick silica etalon to switch between 1645 and 1617 nm oscillation lines. The slope efficiencies measured were 30% and 19% for the 1645 nm and 1617 nm, respectively. Higher efficiency (~47%) of an Er:YAG laser at 1617 nm in-band pumped by a cladding-pumped Er,Yb fiber laser at 1532 nm was recently reported in [6] using intra-cavity etalon providing wavelength discrimination between 1645 and 1617 nm.

Recent progress in volumetric Bragg gratings (VBG) allows using them simultaneously as an output coupler and the wavelength selective element in high power and high output energy solid state lasers systems [7]. The advantages of the VBGs are especially prominent for single frequency lasers when laser line narrowing can be achieved without decrease of the output characteristics. The alternative approach for single-frequency laser oscillation can be based on the injection seeding technique. However, it requires a complex and precision tuning of the laser cavity length so that the oscillating longitudinal mode matches the frequency of the seed laser. Additional approach in the development of highly efficient, high peak power and compact lasers can be based on the passive Q-switching. Transition Metal (Cr) doped II-VI semiconductors (ZnSe, ZnS) due to high $\sigma\tau$ product, absence of excited state absorption, and reasonable (~2 J/cm^2) optical damage threshold are very attractive passive Q- switches for 1.6 μm Er lasers [7,8]. Significant progress in fabrication of affordable, high-quality, low loss Cr:ZnSe media enables additional utility of these crystals as effective gain elements of compact mid-IR tunable laser systems or passive Q-switches for cavities of 1.5-2.1 μm Er, Tm, and Ho lasers [9].

In this paper we demonstrate our recent results of an experimental study on single frequency Er:YAG hybrid lasers operating in CW and Q-switched operation modes. We demonstrate the slope efficiencies of 75% (narrow-linewidth multimode) and 20% (single mode) in the active and passive Q-switched regimes of operation, respectively. To the best of our knowledge these are the highest efficiencies demonstrated in passive and active Q-switched modes of operation of the Er:YAG hybrid lasers operating at 1645 nm.

2. Active Q-switching

The Er:YAG rods with Er concentration of 0.25, 0.5, and 1.0 at. % were fabricated to the lengths of 50, 40, and 30 mm, correspondingly (all with 5 mm diameter). All crystals were antireflection coated for 1.5-1.7 μm spectral range at normal incidence. By testing the crystals in several resonator designs we found experimentally that the optimal rod for obtaining highest slope and optical efficiencies was the 0.5% 40 mm laser crystal. As a pump source we used a commercially available 20 W Er fiber laser with polarized oscillation at 1532 nm wavelength, whose fiber was terminated by a Faraday isolator and collimator (ELR-20-1532.6-LP, IPG Photonics).

In order to obtain highly-efficient, narrow-linewidth operation of the actively Q-switched Er:YAG laser we have chosen a linear cavity laser design with a narrow-band VBG operating as the output coupler. The VBGs have a number of unique properties making them very convenient for obtaining high-energy, pulsed, narrow-linewidth laser radiation: (a) these gratings demonstrate very high optical damage threshold and reliably operate when exposed to high average and peak power laser radiation; (b) VBGs effectively stabilize the laser output wavelength near the center of their bandwidth profile; (c) there is an opportunity for wavelength tuning and for stabilization of the laser output by precision temperature control of the gratings; (d) utilization of sufficiently narrow-bandwidth VBGs lead to the SLM laser operation without any additional intracavity dispersive elements; (c) the use of a Bragg grating as an output coupler allows for a very simple and inexpensive design of the laser cavity, which significantly simplifies laser initial alignment and packaging. In our

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experiments we used VBG samples with diffraction efficiencies of approximately 76% at the Er:YAG oscillation wavelength of 1645 nm and grating bandwidth of 0.14 nm (manufactured by "Optigrate").

The simplest and most efficient laser resonator scheme is based on a folded semi-concentric cavity design shown schematically in Fig. 1 and works as follows. The pump beam is focused into the gain element by a 200 mm pump lens through a dichroic flat input mirror (AR@1532 nm, HR@1645 nm at 45° incident angle). The fluorescence and transmitted pump radiation hits the OC Bragg grating being installed at a minimum possible distance (5 mm) from the output facet of the gain element. The AR coated grating retroreflects about 76% of the lasing wavelength radiation back into the cavity and completely transmits the remaining pump light (the transmitted pump is further separated from the laser radiation by two additional external dichroic mirrors, not shown in Fig. 1). For active Q-switching, a quartz 50 mm Brewster-cut AOM Q-switch is installed into the second leg of the folded cavity. The Q-switch is positioned as close to the input dichroic mirror as possible to increase the overlap of the laser mode and the sound wave, and thus provides the highest diffraction efficiency at the minimum possible RF power. The laser resonator is terminated by a 250 mm end mirror located at approximately 220 mm from the output coupler. It must be mentioned here that the optimal focal length of the pump lens and the position of the spherical end mirror were found experimentally for obtaining the highest possible optical efficiency of the laser.

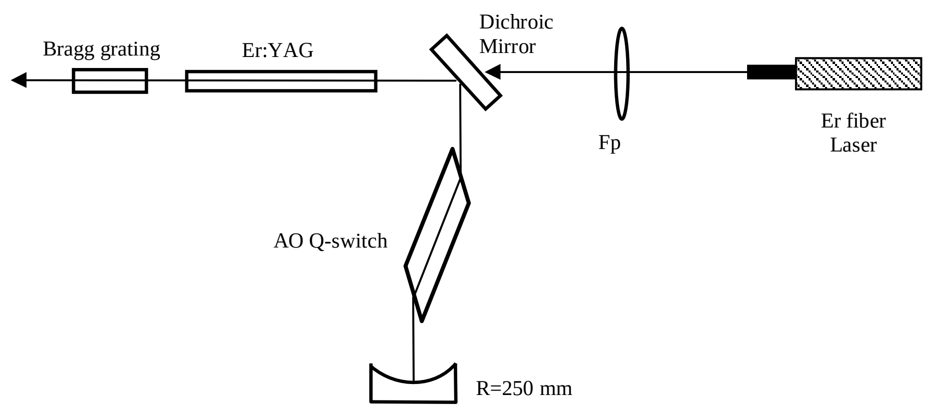

Fig. 1. Optical scheme of the optimal Er:YAG laser linear cavity with Bragg grating output coupler.

The input-output power characteristics of the laser are shown in Fig. 2, where the operation of the Er:YAG linear laser with the AOM Brewster-cut Q-switch in the cavity in the CW (Q-switch is off) and Q-switched (Q-switch is on at 10 kHz repetition rate) regimes are shown. One can see from Fig. 2 that the Q-switch conversion efficiency (with respect to the CW regime of operation) is ~98%. In the Q-switched regime of operation at 10 kHz repetition rate the laser generates up to 1.1 mJ output energy at 19.5 W pump with 75% slope-, and 59% real- optical efficiencies, respectively.

The average output spectrum was measured over 2000 pulses and its width at FWHM was equal to 0.03 nm that corresponds to about 5-6 longitudinal modes. However, single pulses reveal 1-2 longitudinal modes and the relatively broad average spectral width results from pulse-to-pulse wavelength jitter, which was approximately 5 times smaller than the Bragg grating FWHM bandwidth. The 2-longitudinal mode beating could be observed in the time-resolved measurements of the single-pulse temporal profiles (with a sub-nanosecond optical detector). The analysis of the mode-beating spectrum of single laser pulses is shown in Figs. 3(a)-3(b). One can see in Fig. 3(a) that the laser operates at 2 longitudinal modes ~70% of the time, and operates in the SLM regime continuously over 30% of statistically significant number of pulses (see Fig. 3(b)). The slow wavelength drift from the center of the Bragg grating bandwidth center results in gradual switching of the laser from SLM to multimode regime of operation. It must be mentioned here that none of the laser elements (except the Q-switch) were thermally or mechanically stabilized.

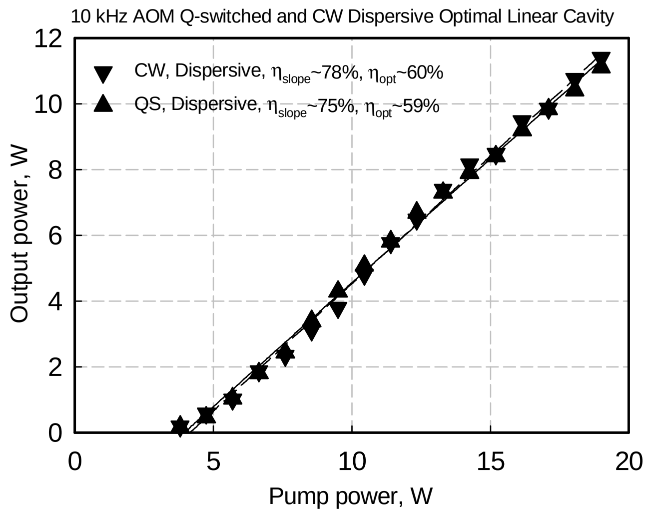

Fig. 2. Er:YAG linear laser cavity Input-Output characteristics in the CW and 10 kHz Q-switched regimes of operation with the AOM Q-switch in the cavity and with the 76% Bragg grating output coupler.

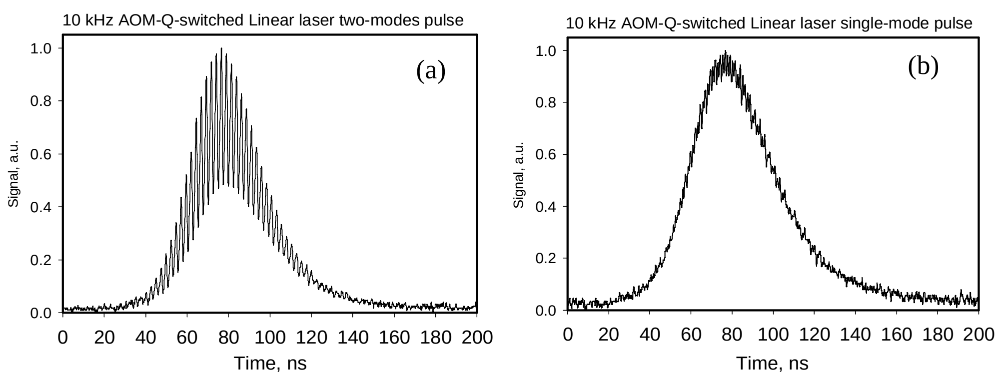

Fig. 3. The pulse shape of the AOM Q-switched Er:YAG linear cavity laser at 10 kHz repetition rate at the maximum average output power of 11.5 W. (a). The mode-beating spectrum shows that the laser operates in two longitudinal modes regime. The FWHM pulse length is ~40 ns. (b). The mode-beating spectrum shows that the laser operates in the single-longitudinal-mode (SLM) regime. The FWHM pulse length is ~43 ns. Long-term statistical analysis of the mode-beating spectrum reveals that the laser operates in 2-lngitudinal mode regime for about 70% of the time and in the SLM regime in 30% of cases.

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4. Passive Q-switching

The main advantage of the active Q-switching is the possibility of obtaining of highly-efficient, high-energy laser source with electronically controlled pulse repetition rate. However, active Q-switching requires efficient thermal management of the laser system, additional RF source (or high voltage driver for EOM modulation), and relatively complex design for obtaining reliable SLM operation of the laser. An alternative approach for obtaining high repetition rate SLM pulsed laser source consists in using a saturable absorber for passive Q-switching. An important feature of the passive Q-switch regime is a very long build-up time of the oscillation pulses as compared to the active Q-switching operation mode. That results in significant narrowing of the spectral width of the oscillation even without additional spectral selector. Another great advantage of passively Q-switched lasers is simplicity (and thus the cost) of their design. Recently, the technology for fabrication of Cr doped ZnSe crystals with a uniform chromium distribution and low parasitic loss was reported [9]. The broad mid-infrared absorption band in Cr:ZnSe crystals is centered at 1780 nm with absorption cross-sections of 49×10^{-20} cm^2 at 1.6 µm. Negligible excited-state absorption losses makes this crystal very attractive for passive Q-switching of the Er lasers.

The schematic diagram of the developed passively Q-switched Er:YAG laser is shown in Fig. 4. The 5 mm pump beam from a 15 W ELM-15-1532 unpolarized Er fiber pump laser is focused into the 1%, 30 mm Er:YAG crystal with a 400 mm focusing lens through the 45° dichroic pump mirror. The stable laser cavity is formed by a flat 100% end mirror, a 75 mm intracavity lens, and 75.5% Bragg grating as the output coupler. The Cr^{2+}:ZnSe flat crystal with the transmission of 95% at 1.55 µm is used as the passive Q-switch and intracavity polarizer. The crystal is installed at the appropriate Brewster angle and is positioned along the optical axis of the laser cavity between the intracavity lens and the end mirror for optimal performance of the laser. The Cr:ZnSe Q-switch has a very small absorption and thus doesn't require an active cooling, so it is mounted in a flat aluminum holder for conductive heat removal.

The input-output characteristics of the passively Q-switched Er:YAG laser are shown in Figs. 5(a)-5(b). One can see in the Fig. 5(a) that the laser demonstrates 20% slope efficiency with the output power approximately 2.5 times higher than previously reported record in Ref. [8]. In Fig. 5(b) one can see the output energy vs pump power. As the pump power grows, the Q-switched laser repetition rate changes from approximately 0.67 to 7.14 kHz. At the pump powers close to the threshold the repetition rate change is relatively irregular, however, as the pump and the average output powers increase, the repetition rate changes linearly.

In Fig. 6(a) one can see time-resolved measurements of the laser pulses performed with a sub-nanosecond optical detector at the highest pump power of 15 W and repetition rate of ~7 kHz, and Fig. 6(b) shows the pulse train of the laser. From Fig. 6(a) one can see that the laser demonstrates a 65 ns pulse length and is clearly operating in the single-longitudinal-mode regime without any observable mode-beating spectrum. It must be mentioned here that the SLM regime of operation is observed at all pump/output powers when the laser is passively Q-switched.

In overall, the SLM passively Q-switched laser has a very simple construction and thus can be manufactured with very compact design. The main advantage is that the laser doesn't require any additional electronic controllers (including thermal management system) so that the laser can be manufactured as a convenient compact attachment for commercially available high power Er fiber lasers.

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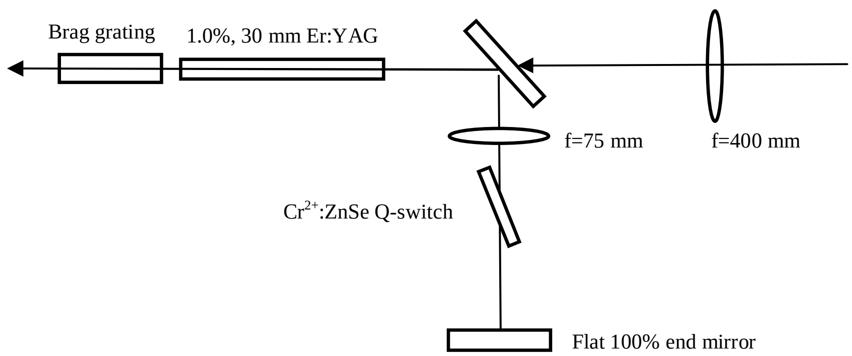

Fig. 4. Schematic diagram of the optical scheme of the passively Q-switched Er:YAG laser.

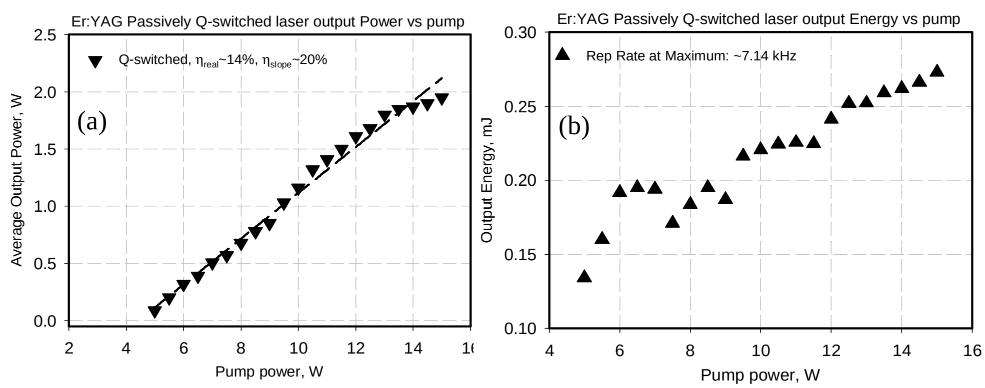

Fig. 5. (a). Average output power vs pump of the passively Q-switched Er:YAG SLM laser. (b). Output energy vs pump of the passively Q-switched Er:YAG SLM laser. The pulse repetition rate changes from 0.67 to 7.14 kHz as the pump power is increased.

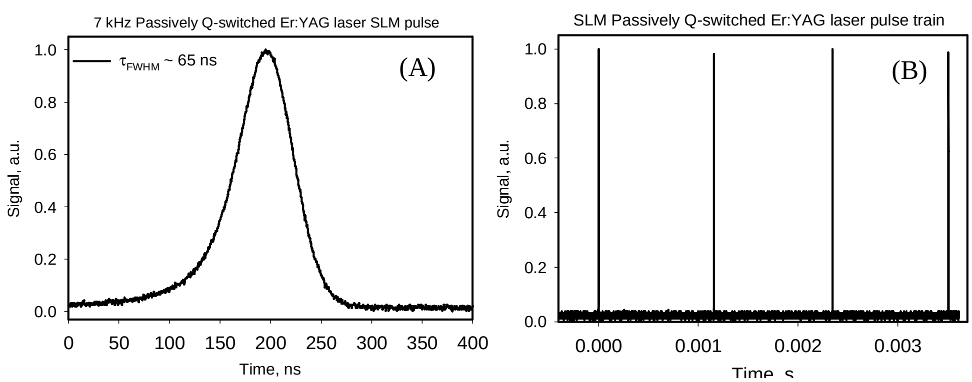

Fig. 6. (a). Time-resolved trace of the output pulses. The laser is clearly operating in single-longitudinal mode regime with the pulse length at FWHM of ~65 ns. (b). The pulse train of the passively Q-switched Er:YAG laser.

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5. Conclusion

In conclusion, we have demonstrated highly-efficient, high power, high repetition rate, narrow-linewidth actively Q-switched Er:YAG laser with Bragg grating output coupler and reported record laser efficiencies (75% slope and 59% real) with an opportunity for control of the oscillation wavelength and reduced pulse-to-pulse wavelength jitter. We have also demonstrated a stable single longitudinal mode operation of Cr:ZnSe passively Q-switched Er:YAG laser with a record of 2 W average output power at 7 kHz repetition rate. In all our experiments we did not observe thermal roll-off of the output characteristics. Further power scaling of the Er-fiber pumped Er:YAG lasers can be obtained by using single oscillator design with higher power pump fiber lasers.

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