Cr-ZnSe Passively Q-switched fiber-bulk Ho:YAG hybrid laser

Yuri Terekhov [a], Igor S. Moskalev [a], Dmitri V. Martyshkin [a], Vladimir V. Fedorov [a], and Sergey B. Mirov *[a, b]

[a] Center for Optical Sensors and Spectroscopies and the Department of Physics, University of Alabama at Birmingham, CH 310, 1300 University Blvd., Birmingham, AL 35294, USA;

[b] Photonics Innovations, Inc, 1500 1st Ave N, Unit 39, Birmingham, AL 35203, USA

ABSTRACT

The objective of this work was to develop a compact and efficient Tm-fiber-Ho:YAG, hybrid laser passively Q-switched by Cr:ZnSe saturable absorber. We used a folded semi-hemispherical 10 cm long cavity with a plane output coupler and a 0.5 m concave high reflector. In these experiments we studied the performance of two high optical quality Cr:ZnSe crystals as saturable absorbers with initial transmissions of 93.9% and 70% at 2.1 µm. With the 93.9% transmission crystal, passive Q-switching was realized with a maximum output power of 5 W, pulse energy of 0.5 mJ, pulse duration of 150 ns, and Q-switched-to-CW-mode extraction efficiency of 60%. With the 70% transmission crystal, passive Q-switching was achieved with a 75% Q-switched-to-CW-mode extraction efficiency, pulse energy of 3 mJ, and duration of 7ns. The laser demonstrated sustained damage-free, TEM_{000} operation with 0.5 MW of peak power showing promise for applications requiring high-peak-power, diffraction-limited beams, and single-frequency regimes of operation.

Keywords: Passive Q-switching, Cr:ZnSe, Ho:YAG laser, Tm-fiber laser

1. INTRODUCTION

Holmium lasers operating in CW and Q-switched (Q-SW) regimes with high output power and high pulse energy in the eyesafe two-micron spectral region proved to be convenient sources of near-IR radiation for a variety of scientific, medical, and military applications. It has been shown that direct resonant laser pumping of the Ho $^5I_7$ manifold, featuring high cross-section and long fluorescence lifetime (~ 13 ms), results in a high energy storage capability and efficient Q-switched operation of holmium lasers [1-6]. This resonant excitation scheme of Ho lasers commonly uses Tm-laser based pump sources and due to a small quantum defect between Tm radiation (1.96 µm) and Ho emission (2.1 µm) simplifies the thermal management of gain material, reduces temperature sensitivity of gain and enables high short-pulse extraction efficiency. For example, in [2], 50-mJ pulses at 60 Hz were achieved from an actively Q-switched 2.09-µm Ho:YAG oscillator resonantly pumped by a diode-pumped Tm:YLF laser. Among a number of publications on holmium lasers pumped by Tm-fiber lasers, only a few of them are devoted to passive Q-switched regimes of operation. The objective of this work was to develop a compact and efficient TEM_{000} Tm-fiber-Ho:YAG, hybrid laser passively Q-switched by Cr:ZnSe saturable absorber.

2. ACTIVELY Q-SWITCHED HO:YAG LASERS

As shown in [7], the performance of 0.5% 5 cm long Ho:YAG over a range of temperatures -15÷+20 °C featured practically constant output of Ho:YAG laser with a mild slope of 0.17 mJ/°C. Hence, we believe, that low quantum defect heating (~9%) in the Ho:YAG, low concentration of Ho and relatively long length of the YAG crystal used result in a reduced thermal loading and mitigate the advantages of athermal behavior of Ho:YLF gain material with respect to YAG host. The YAG crystal with Ho concentration of 0.5% was grown at Scientific Materials. The rod fabricated to a length of 50 mm with antireflection coating at 1.9-2.15 µm spectral range was mounted in a conductively cooled Cu finger, attached to air-cooled thermoelectric cooler.

A schematic diagram of the Ho:YAG laser, optimized for maximum efficiency in CW and high rep rate Q-switched regimes of operation, is depicted in Figure 1. We used a folded cavity configuration, which allowed us to easily adjust

* mirov@uab.edu

the cavity length for a good Tm-to-Ho mode match. The laser resonator consists of a 0.5 m concave high reflector and a flat output coupler with the optimum reflectivity of 50%. The collimated output beam from the Tm-fiber laser was focused through a dichroic flat folding mirror by a 20 cm lens to fill the mode volume of Ho:YAG laser cavity. Q-switched operation was achieved with an acoustooptic modulator with the acoustic aperture of 0.8 mm and length of 35 mm.

The Q-switch material was fused silica, and both input and output surfaces had antireflection coating at oscillation wavelength. The passive insertion loss of the Q-switch was about 0.5%. In non-polarized cavity, the maximum output energy in Q-switched mode was limited by parasitic free running oscillation due to low active losses for non-polarized radiation in the acousto-optic modulator. In order to provide oscillation in the linear polarization a plane-parallel CaF_2 Brewster plate was used. Operating the Q-switch at 40.7 MHz and RF power of 15W we were able to achieve 60% diffraction loss. The Q-switch was mounted on a conductively cooled Cu finger, attached to air-cooled TEC and its temperature was kept at 20^{o}C.

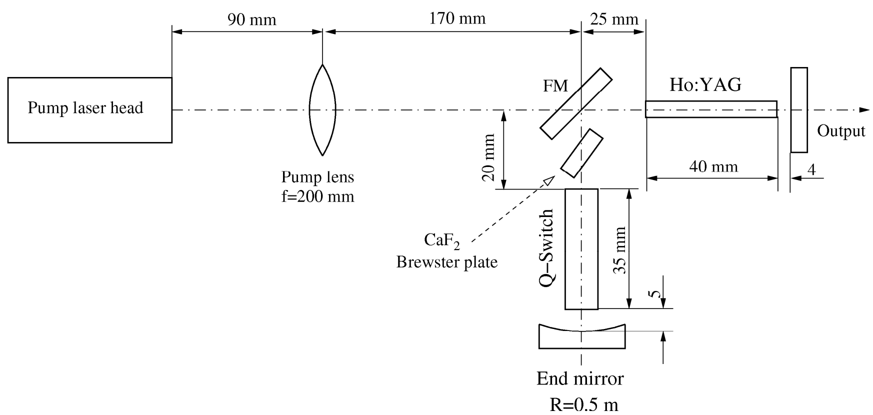

Fig. 1. Optical scheme of the highly-efficient Ho:YAG laser

The graphs in Figure 2 show the dependencies of the average output power on the pump power, incident onto the Ho:YAG crystal, for CW and 10 kHz Q-switched regimes of operation. The graphs contain four independent experimental data sets and the cumulative data points are linearly fitted to obtain the slope efficiencies. As one can see from the graphs in Figure 7, the slope efficiencies for the CW and Q-switched regimes of operations are in excess of 50%.

In order to obtain the highest pulse energy in Q-switched regime of operation one has to decrease the repetition rate until it becomes smaller than $1/\tau$, where τ is the lifetime of the excited state equal to ~10 ms for 0.5% Ho:YAG, which gives a 100 Hz repetition rate. Unfortunately, the available dichroic folding pump mirror (FM in Figure 1), which has complex AR/HR coatings to provide 100% reflectivity at lasing wavelength and 95% transmission of the pump radiation, has a very low damage threshold and is burned at repetition rates less than 5 kHz. One way to address this problem is to increase the mode size on the folding mirror, reducing the power density at its surface. For this reason, we have modified the original laser scheme by increasing the cavity length moving the folding mirror as close as possible to the spherical reflector.

A schematic diagram of the high energy Ho:YAG laser is shown in Figure 3. The focal length of the pump lens and its position, as well as the position of the Ho:YAG crystal, were found experimentally for obtaining the highest output energy without burning the folding mirror. The Q-switch was installed near the laser mode waist where it provides the highest loss.

The most efficient Q-switch performance in this case was obtained with a 30% output coupler. The oscillation threshold was about 13 W of pump power. The maximum achieved output energy was 15 mJ at 100Hz repetition rate and 22 W pump power, with sustained damage-free operation of the laser. The slope efficiency was about 17%, which shows that at 25 W of pump power up to 20 mJ of output energy could be achieved. The limiting factors were the available maximum pump power and the low damage threshold of the folding dichroic mirror. The minimum pulse duration was 17 ns at 100 Hz and increased to 20 ns at repetition rates above 1 kHz. The output parameters at different repetition rates are summarized in the Table 1.

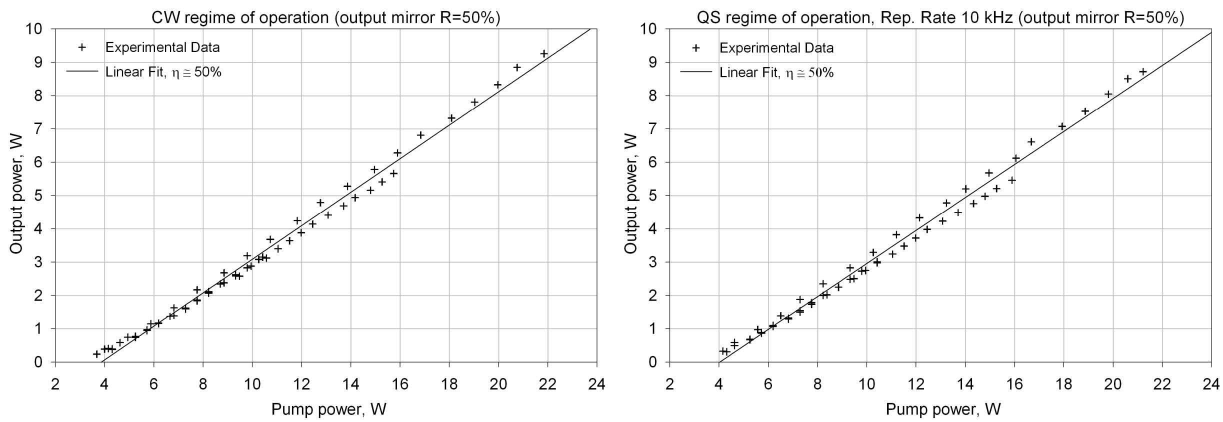

Fig. 2. Average output power vs incident pump power in CW (left graph) and 10 kHz Q-switched (right graph) regimes of operation. The graphs contain four experimental data sets. The linear fits of the experimental data show the slope efficiencies of 50% for both CW and Q-switched regimes of operation

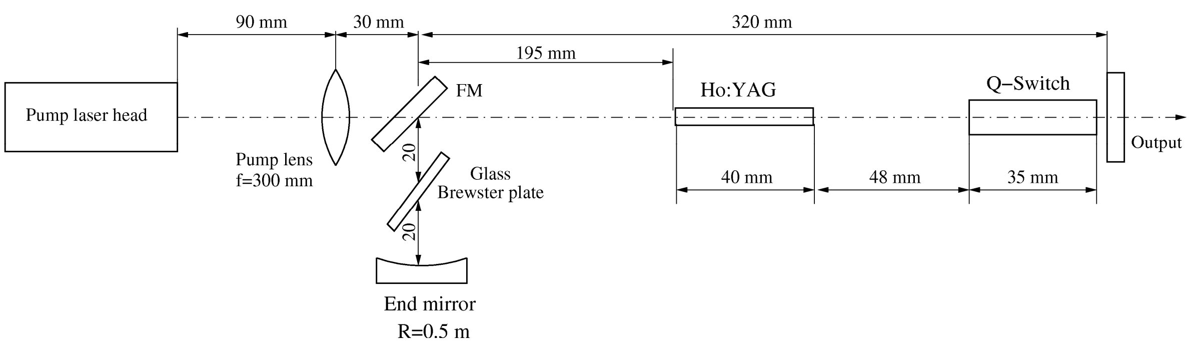

Fig. 3. Optical scheme of the high-energy Q-switched Ho:YAG laser

Table 1. The maximum output parameters of the Q-switched Ho:YLF laser with output coupler R=30%

Rep.rate, Hz	Pulse energy, mJ	Output power, W
100	15	1.5
250	6.9	1.7
500	5.3	2.8
1000	3.5	3.5
2500	1.6	4.0
5000	0.8	4.0
10000	0.3	3.3

3. PASSIVELY AND ACTIVELY Q-SWITCHED HO:YAG LASERS

The basic condition for a good passive *Q* switch is that its cross section of absorption greatly exceed the cross section of emission of the gain material used in the cavity ($\sigma_{abs}>\sigma_{em}$). More general condition should include the intra-cavity beam areas at the absorber and gain media ($\sigma_{abs}/A_{abs}>\sigma_{em}/A_{gain}$). The published absorption cross-section spectrum of Cr^{2+}:ZnSe and absorption and emission cross-sections spectra of Ho:YAG crystal are shown in the Figure 4. As one can see from the Figure 4 the values of absorption cross-section of chromium ions in ZnSe at 2.1 µm more the 10 times exceeds the value of emission cross-section of holmium in YAG crystal.

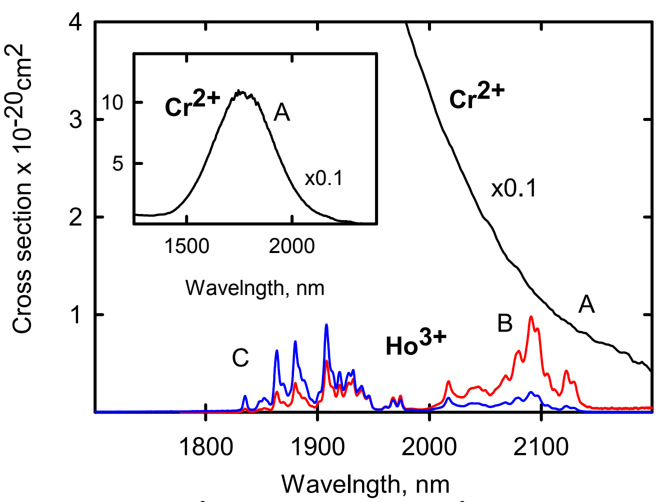

Fig.4 Absorption cross-sections of Cr^{2+} ions in ZnSe (A) and Ho^{3+} in YAG crystals (C); emission cross-section of the Ho^{3+}:YAG crystals (B).

In our experiments, a Cr^{2+}-doped ZnSe crystal was used as a saturable absorber instead of a glass Brewster plate. The passive Q-SW crystals had a transmission of 96.7% and 70% at a 2.1µm Ho emission wavelength. The output coupler was a plane mirror with 50 % reflectivity. The most efficient short laser cavity used for passive Q-switching is shown in the Figure 5.

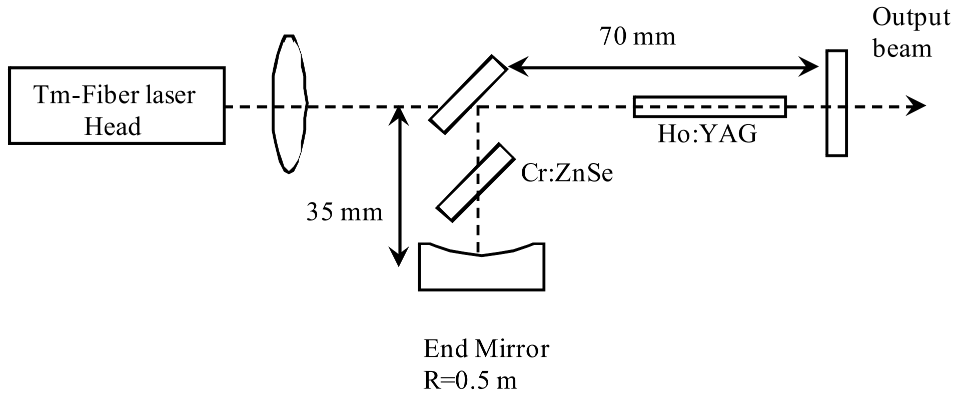

Fig. 5. Optimized cavity of a passively Q-switched Ho:YAG laser.

Figure 6 features input-output characteristic of the passively Q-switched Ho:YAG laser with the 70% transmission of the Cr:ZnSe passive crystal. The obtained output power reached the level of 4.1W at 16.6W incident pump with 39% slope- and 25% real optical efficiencies. For comparison, the CW oscillation of the Ho:YAG laser with 45% slope efficiency was measured in the same cavity without Cr:ZnSe crystal.. The slope efficiency of operation in the passively Q-switched regime with respect to CW operation was as high as 84%. To the best of our knowledge, it is the highest value for passively Q-switched Ho:YAG laser efficiency documented in the literature.

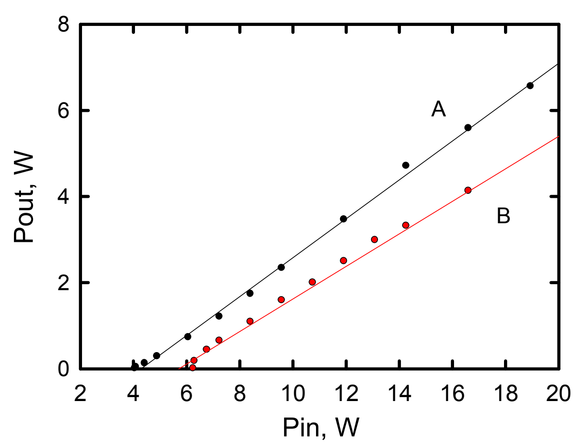

Fig. 6 Ho:YAG oscillator output power, with (A) and without (B) Cr:ZnSe *Q*-switch, as a function of pump power.

Figure 7 represents a characteristic train of Q-Switched Ho:YAG pulses obtained for input power of 8W. As one can see for 8W pump power, the passively Q-switched Ho:YAG laser operates at repetition rate of 500Hz and features a stable output pulse energy of 1.7 mJ.

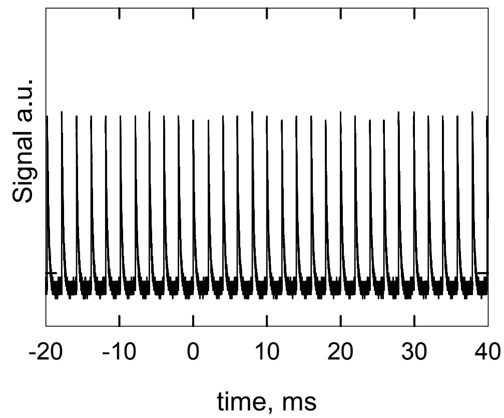

Fig. 7 Train of output pulses of passively Q-SW Ho:YAG laser at pump power of 8W and output pulse energy of 1.7mJ

According to a simple model of passively Q-switched regime of operation, the pulse energy is defined by the initial transmission of the absorber and is not sensitive to the variation of the pump power. However, as one can see from the Figure 8A, the output energy of the passively Q-switched Ho:YAG laser increases from 1.5 mJ near laser threshold up to 3 mJ at 16 W of the pump power. Figure 8B shows the repetition rate of passively Q-switched Ho:YAG laser versus incident pump power. The repetition rate of the laser oscillation with 50 % output coupler increases from ~100Hz art laser threshold (6W) to 1500 Hz at 16.6W of the pump power.

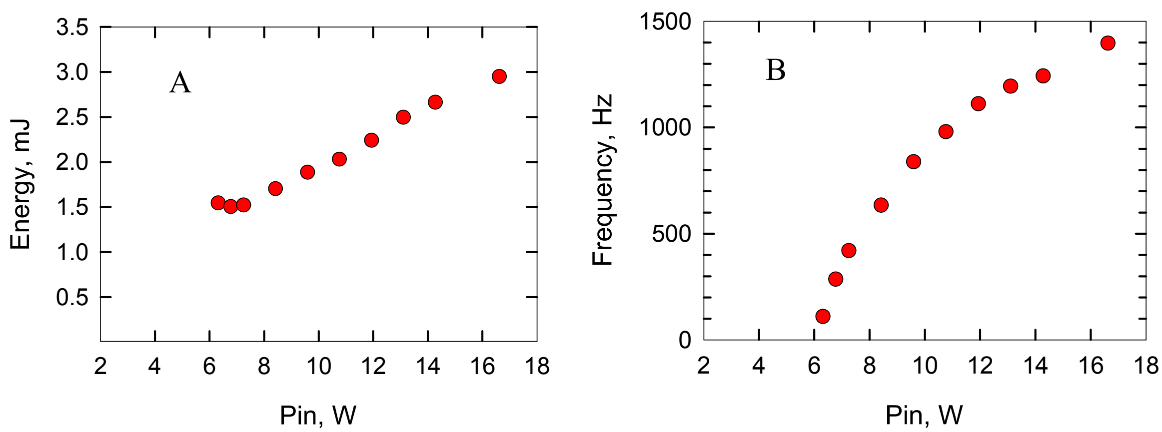

Fig. 8 Output energy (A) and repetition rate (B) of the passively Q-switched Ho:YAG laser

It is well documented in the literature, that because of a relatively long oscillation build-up time passive Q switching usually enables a longitudinal-mode selection. It can result in a single frequency regime of oscillation achieved even without installation of any additional selective intracavity elements. The confinement parameter for single frequency oscillation was suggested in paper [8]. It was demonstrated in this paper that to ensure single-frequency operation the difference in build-up time between any two longitudinal modes of the laser resonator should be comparable with or greater than the laser pulse duration. To indirectly verify whether we obtained a single frequency regime of oscillation in passively Q-Switched cavity, the temporal profile of the output laser pulses was measured with a fast detector with temporal response shorter than the longitudinal-mode beating interval in the studied cavities. The oscillation pulses from the passively Q-switched cavity showed no evidence of mode beating associated with multimode operation (see Figure 9A), whereas pulses from the actively Q-switched cavity demonstrated a strong mode beating (see Figure 9B).

With the high 93.9% transmission crystal, passive Q-switching was realized with a maximum output power of 5 W, pulse energy of 0.5 mJ, pulse duration of 150 ns, and Q-switched-to-CW-mode extraction efficiency of 60%.

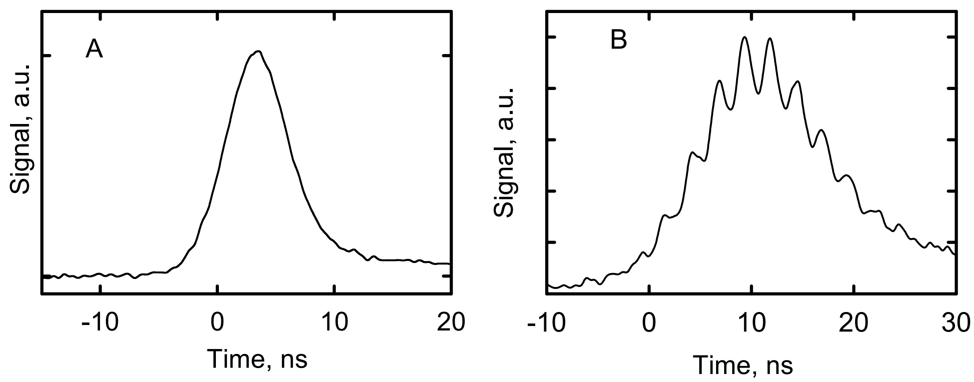

Fig. 9 Temporal profile of the passively (A) and actively (B) Q-switched output pulses.

4. CONCLUSIONS

We report a development of compact and efficient passively and actively Q-switched Tm-fiber-Ho:YAG, hybrid laser. For the cavity optimized at high repetition rate, the laser efficiencies of the free-running CW and fused silica acousto-optical actively Q-switched operation modes were equal to each other and exceeded 50%. In the cavity optimized for low preparation rate, we demonstrated output energy as high as 15 mJ at 100Hz repetition rate. It was demonstrated that Cr:ZnSe crystals are efficient passive Q-switches for the cavities of Ho:YAG laser. A single frequency regime of Ho:YAG lasing was achieved in Cr:ZnSe passive Q-switched regime of operation without any additional intracavity selective elements. in The maximum output energy of 3 mJ was achieved in the passively Q-switched Ho:YAG laser cavity with efficiency as high as 84% with respect to free-running CW laser efficiency.

5. ACKNOWLEDGEMENT

We are grateful to our colleagues and collaborators from IPG Photonics Corporation V. Gapontsev, D. Gapontsev, N. Platonov, and A. Babushkin for useful discussions and support of this project. This material is partially based upon work supported by the IPG Photonics Corporation –UAB Research Agreement and NSF grant EPS-0814103.

REFERENCES

[1] D.W. Hart, M. Jani, N.P. Barnes, "Room-temperature lasing of end-pumped Ho:$Lu_3Al_5O_{12}$", Optics Letters 21, 728-730 (1996).

[2] P.A. Budni, M.L. Lemons, J.R. Mosto, and E.P. Chiklis, "High-power/high brightness diode-pumped 1.9-µm Thulium and resonantly pumped 2.1-µm Holmium lasers", IEEE J. on Selected Topics in Quantum Electron., 6, 629-635 (2000).

[3] P.A. Budni, L.A. Pomeranz, M.L. Lemons, C.A. Miller, J.R. Mosto, E.P. Chiklis, "Efficient mid-infrared laser using 1.9-µm pumped Ho:YAG and $ZnGeP_2$ optical parametric oscillators", J. Opt. Soc. Am. B, 17,723-728 (2000).

[4] A. Dergachev, P.F. Moulton, "High-power, high energy diode-pumped Tm:YLF-Ho:YLF-ZGP laser system", OSA Trends in Optic and Photonics Vol.83, 137-141 (2003).

[5] E. Lippert, G. Arisholm, G. Rustad, and K. Stenersen, "Mid-infrared laser source with high power and beam quality" Applied Optics, 45, 3839-3845 (2006).

[6] I. S. Moskalev, V.V. Fedorov, S.B. Mirov, A. Babushkin, V.P. Gapontsev, D.V. Gapontsev, N. Platonov, "Efficient Ho:YAG Laser Resonantly Pumped by Tm-Fiber Laser", in Advanced Solid-State Photonics 2006, TuB10, Technical Digest on CD-ROM (The Optical Society of America, Washington, DC), 2006.

[7] P.A. Budni, C.R. Ibach, S.D. Setzler, E.J. Gustafson, R.T. Castro, E.P. Chicklis, "50-mJ, Q-switched, 2.09-µm holmium laser resonantly pumped by a diode-pumped 1.9-µm thulium laser", Optics Letters 28, 1016-1018 (2003).

[8] Y. Isyanova, D. Welford, "Temporal criterion for single-frequency operation of passively Q-switched lasers", Op. Let. 24, 1035-1037(1999).