Diode-Pumped and passively Q-switched Er:YAG Laser emitting at 1617 nm

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Adrien Aubourg[1,2], Julien Didierjean[2], Nicolas Aubry[2], François Balembois[1], Patrick Georges[1]

[1]Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ Paris-Sud - 2 Avenue Augustin Fresnel, 91127 Palaiseau Cedex, France
[2]Fibercryst - Parc d'activité Wilson, Bât A1, 31 Rue Wilson, F-69150 Decines-Charpieu, France

ABSTRACT

We present laser operation of a 750 µm diameter Er:YAG single crystal fibers pumped at 1470 nm. Laser output performances are numerically simulated, experimentally measured and compared. In Passive Q-switch regime, we obtained pulse energy of 180 µJ around 500 Hz at 1617 nm without any spectral selecting element. Pulse duration is 33 ns. By controlling the saturable absorber temperature, we succeeded to improve the output energy up to 270 µJ. These results show the interesting potential of Er:YAG single crystal fiber for compact and low power consumption rangefinders.

Keywords: Er:YAG, Solid-State laser, Passive Q-switch, Diode pumped laser

1. INTRODUCTION

One candidate as a laser source for applications requiring eye-safe emission in the atmosperic transmission window, namely lidar, telemetry or active imaging, is resonantly pumped Er:YAG lasers. These systems has an extended choice of pump configurations. Indeed, depending on requirements, one can use Er:Yb fiber laser at 1533 nm [1], or laser diodes at 1533 nm [2] or 1470 nm [3]. For these pump setups, the 10 mJ range is already achieved in actively Q-switch operation around 100 Hz.

For some military applications, the total electrical consumption of the laser source is a critical specification. Hence, the use of a fiber laser or a high power diode as a pump source is prohibited. Similarly, an acousto-optic modulator (AOM) or an electro-optic modulator (EOM) cannot be use to generate Q-switched giant pulses as these systems consume at least few hundreds watts of electrical power. In these context, the use of a saturable absorber and a low power pump diode seems a good candidate for a laser emitter with a electrical consumption around 100W.

To improve the range of the emitter without increasing pulses energy, one solution is to obtain laser operation at 1617 nm instead of 1645 nm because of residual absorption of methane at the latter wavelength. Unfortunately, the natural emission of Er:YAG is 1645 nm as it requires a minimum population inversion of 9% to reach transparency, compared with 16% for transparency at 1617 nm. A wavelength shift can occur thanks to an intra-cavity etalon [4], or a Cr:ZnSe saturable absorber [5] as its absorption cross-section is increasing between 1617 nm and 1645 nm.

We present a passively Q-switched Er:YAG laser with a low diode-pump power of 14W at 1470 nm. Our target is to limit the overall electrical consumption to around 100 W to get few hundreds of µJ range pulse energy. We highlight the need to thermally control the Cr:ZnSe saturable absorber to improve output energy. We already presented a passively Q-switch cavity with 40 W of pump power [6], but the decreased pump power by a factor of 3 is a challenge for a quasi-three level system with an intra-cavity saturable absorber.

2. NUMERICAL SIMULATIONS OF Q-SWITCHED Er:YAG CAVITIES

2.1 Description of the numerical simulation

Because of the fiber-coupled diode pumping, the pump beam has a high divergence which greatly decrease the overlap with the laser signal, and so the overall efficiency. One may use a high-doped and short gain crystal, but the efficiency would be also impacted because of thermal effects. One solution is to use a single crystal fiber (SCF). Its low diameter (1 mm or less) can confine the pump beam thanks to total internal reflections, greatly increasing the overlap with the laser beam, and improving the population inversion along the crystal axis raise the efficiency and favour the emission at 1617 nm.

First, the pump density inside the whole volume of the gain crystal must be calculated. This is done by casting rays according to the pump setup (pump spot diameter, laser diode brightness...) and propagating them along the crystal. When hitting the crystal border, a new direction for the ray is calculated according to its position. Despite the high symetry of the cylindrical geometry, this process must be done in a 3D matrix. Fig. 1 shows the result of a raycasting inside an undoped YAG crystal. At this step, one can evaluate the pump density, the heat generation and the population inversion for each point of the crystal from the rate equations.

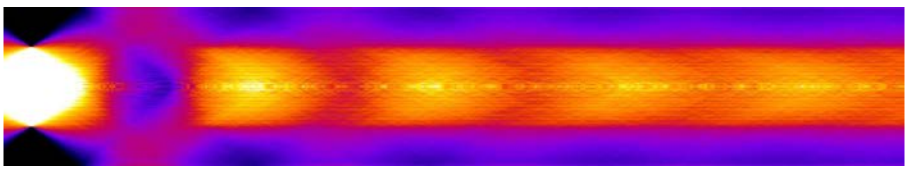


Fig. 1 - Pump density inside an undoped YAG single crystal fiber, 6 mm long, 0.8 mm diameter. There is a noticeable confinement of the pump density in the center of the crystal, thus improving the population inversion along the path of the laser signal.

To simulate a Q-switched cavity, a temporal resolution of the rate equations has to be done. The idea, already described in [7], is to monitor and refresh the total number of photons inside the cavity. With this value, one can know the photon density in the crystal volume to compute the new population inversions (spatially resolved) and the evolution of the photon number. Cross-sections for Er:YAG are given in [8]. Without temporal modulation of losses, this method will give the output power in continuous wave (CW) operation. Hence, time-dependent losses are inserted to simulate the cavity in active Q-switched regime.

To simulate the passive Q-switch operation, we assume the Cr:ZnSe to be a 2-levels system, but with a saturated transmission of 98.5% while totally bleached (it can't be 100% because of excited state absorption). The lifetime is fixed at 6 µs. Cr:ZnSe cross-sections at 1645 nm and 1617 nm don't depend on the temperature. Hence, the simulation doesn't take into account spectroscopic changes of ground state and excited state cross-sections with the temperature. Indeed, to the far of our knowledge, there are no published measurements of these evolutions.

2.2 Comparison in the case of active Q-switch

To validate the simulation, we compared its result to an actively Q-switched Er:YAG cavity depicted in Fig.2. It uses a 0.5 at.% Erbium doped YAG crystal, 30 mm long with a diameter of 750 µm. It is embedded inside a 3 mm thin copper plate with the Taranis technology from Fibercryst to ensure a very good thermal dissipation of the crystal. The copper plate is water-cooled at 12°C. The acousto-optic modulator (AOM) uses a 6 cm long quartz crystal and 2 piezo-electric actuators. M1 mirror is a dichroïc meniscus with a radius of curvature of 50 mm. It has high reflectivity for the laser over the 1600-1650 nm range and high transmission for the pump over the 1440-1500 nm range. The output coupler M2 has a radius of curvature of 100 mm and a reflectivity of 80% for both 1645 nm and 1617 nm wavelengths. The cavity length is 140 mm. An 100 µm thin etalon is inserted between the crystal and the AOM to shift the emitted wavelength from 1645 nm to 1617 nm. This design sets the cold-cavity laser waist inside the crystal with a diameter of 220 µm. Compared to the literature, the available pump power is low, hence the diameters of the laser waist and the pump beam spot are reduced to keep a high gain in the crystal. This is unfortunately done at the expense of stored and extractible energy.

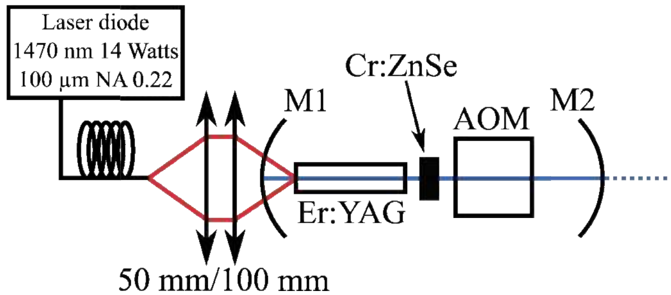
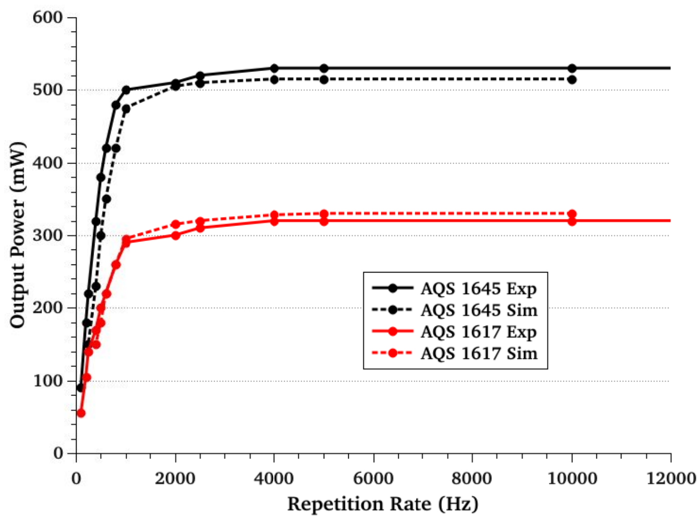


Fig. 2 - Experimental setup of the actively (without the Cr:ZnSe saturable absorber) or passively (without the Cr:ZnSe) Q-switched



cavity.

Fig. 3 - Experimental results (plain) and simulation results (dashed) of the actively Q-switched cavity, at an emitted wavelength of 1645 nm (black) and 1617 nm (red)

The figure 3 displays the simulated and experimental output power of the actively Q-switched cavity versus the repetition rate. Simulations fit well with the experimental output power versus the repetition rate. To really fit both curves, we adjusted the laser beam waist diameter from 210 µm to 230 µm. The power drop at low repetition rate (the extracted energy is capped by the spontaneous emission) is well simulated, with pulse shape and duration as well.

2.3 Expected results in passive Q-switch operation

Before Q-switching the cavity with saturable absorbers, we run the simulation (with three commercialy available saturable absorbers with 85%, 90% and 95% of initial transmissions) to evaluate the expected energy per pulse. Results are shown in Fig. 4.

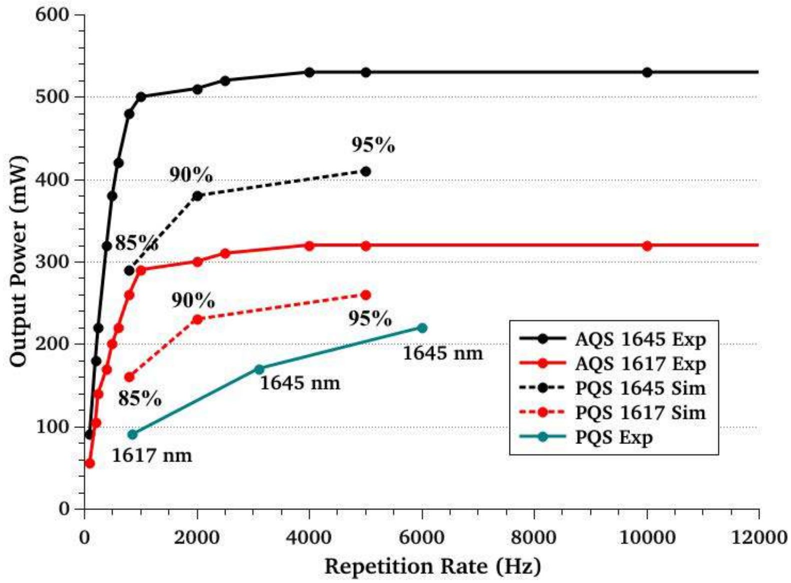


Fig. 4 - Active Q-switch experimental (plain) and passive Q-switch simulated (dashed) mean power versus repetition rate at 1645 nm (black) and 1617 nm (red). Blue line is the experimental output with three saturable absorbers inserted in the cavity with an inactive AOM

A drop of around 20% is expected by Q-switching the cavity from active to passive configuration, and comes from the small residual absorption (2% single-pass) of the saturable absorber. This drop is in accordance with the inserted losses (4%) and the output coupler reflectivity (80%).

3. PASSIVE Q-SWITCH CAVITY WITH THREE DIFFERENT SATURABLE ABSORBERS

3.1 Experimental setup

Cr:ZnSe absorbers with initial transmissions of 95%, 90% and 85% have been consecutively inserted in the same cavity (Fig. 2) between the crystal and the AOM while the AOM is kept inactive to compare the performance in the same conditions. They are anti-reflection coated for both Er:YAG 1.6 µm emissions. First, there was a output wavelength shift from 1645 nm to 1617 nm with the 85% of initial transmission saturable absorber. This effect has already been observed and described in previous publications [6].

3.2 Passive Q-switch with Cr:ZnSe absorbers

From actively to passively Q-switch regimes, a small decrease was expected (Fig. 4) as saturable absorbers insert losses while the Q-switch pulse is building until the saturation intensity is reached. In addition, these crystals exhibit a excited state absorption (ESA) cross-section which limits the maximum saturated transmission. Fortunately, the ESA remains low compared to the ground state absorption (GSA) so the modulation depth is still usable for Q-switch operation.

The upper state lifetime is large (6 µs) towards our 100 ns-range pulse duration and shouldn't impacts the output energy, and the saturation intensity of Cr:ZnSe crystal is easily exceeded as its value is very low (18 kW/cm2). However, we experimentaly observed a decrease of around 65% of the performances from active to passive Q-switch (Fig. 4) instead of 20%, implying a cut of the saturated transmission of the saturable absorbers. In this configuration, pulse energy reached 110 µJ at 1617 nm, with long duration of 40 ns caused by the long cavity.

4. HEAT MANAGEMENT OF THE SATURABLE ABSORBERS

4.1 Heat measurements of Cr:ZnSe saturable absorbers

Although their thermal conductivity is fairly high (16 W/m/K), the form factor (3x3x0.6 mm) and the lack of any heat dissipation system for the Cr:ZnSe crystal may lead to an important heat. Thus, we investigated the temperature elevation of these crystals used as saturable absorber inside an Er:YAG cavity. For this purpose, saturable absorbers were put on Peltier plate to control their internal temperature which was monitored thanks to a thermal camera (Fig. 7).

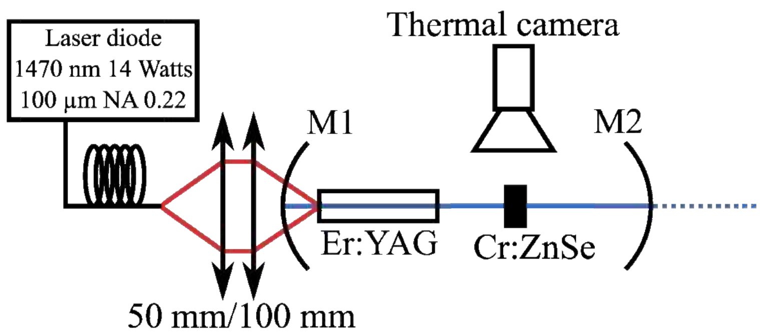


Fig. 7 - Experimental setup of the heat measurement of the Cr:ZnSe. The saturable absorbers are put on a Peltier plate to investigate the dependance of the laser output with its temperature.

We mesured the Cr:ZnSe temperature without any thermal control (Fig. 8). It is measured to be globally higher than 150° C. The slope with the coupler reflectivity indicates that the heat elevation is mainly due to a residual laser absorption of the Cr:ZnSe crystal.

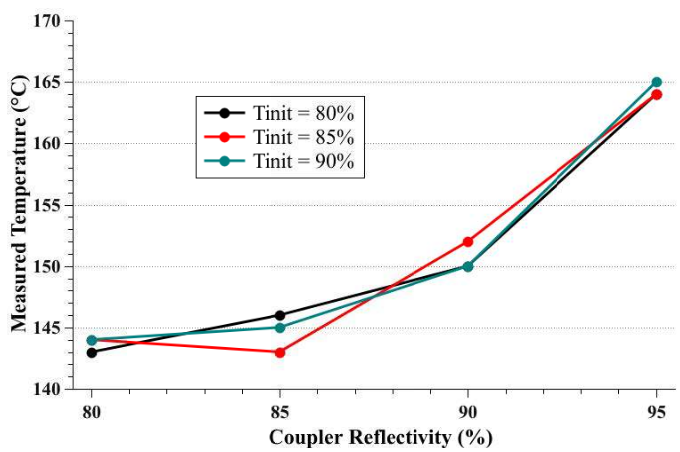


Fig. 8 - Saturable absorbers temperature for different initial transmission and output coupler reflectivity

4.2 Temperature influence on the output performances

Thanks to the Peltier plate and an oven, we tuned the Cr:ZnSe temperature over a large range from 5°C to 220°C. Over all the Q-switched operation range, the energy raised (from 60 µJ to 85 µJ) by cooling the Cr:ZnSe crystal from 150° C (Cr:ZnSe temperature with inactive Peltier plate) to 25° C in case of 90% initial transmission saturable absorber. It goes from 110 µJ to 220 µJ for 85% initial transmission Cr:ZnSe. Such variations lead to different energetic states of the crystal after the pulses, so we also observe slight variations on the repetition rates (Fig. 9). We also noticed a slight decrease of energy for temperature below 25°C, which are not yet well understood.

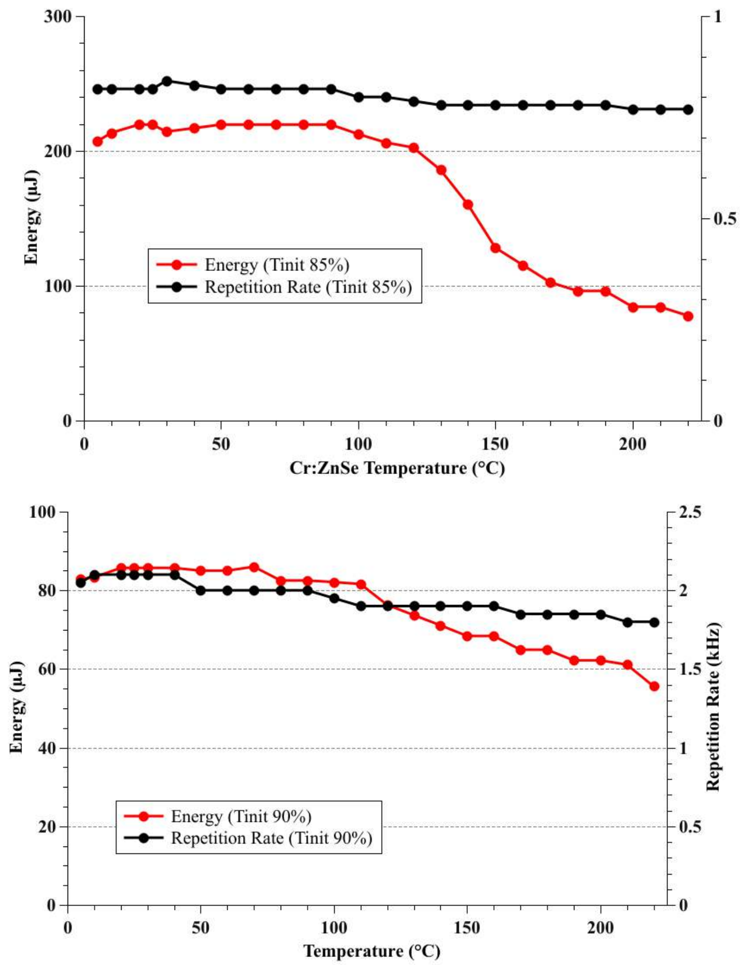


Fig. 9 - Output energy (red) and repetition rate (black) versus Cr:ZnSe saturable absorber temperature

4.3 Origin of energy variations with Cr:ZnSe temperature

Measurements of Cr:ZnSe excited state lifetime with temperature has been done by Sorokina [9] and are reproduced in Fig. 10. The lifetime τ_c decreases a lot from 300 K, from 5.5 µs down to under 1 µs. Stating that the saturation intensity of a saturable absorber is $I_{sat} = 1/(\sigma * \tau_c)$, there is a factor 5, at least, on I_{sat}, leading to a decrease of saturated transmission if the intra-cavity intensity isn't high enough.

For instance, if one has one order of magnitude of effective intra-cavity intensity (150 kW/cm^2) beyond the room-temperature saturation intensity of Cr:ZnSe (15 kW/cm^2), it may not be enough if the Cr:ZnSe cristal is not cooled, as it will have an effective saturation intensity around 75 kW/cm2 at 150°C, which is half the intra-cavity intensity, resulting in additional losses in the cavity.

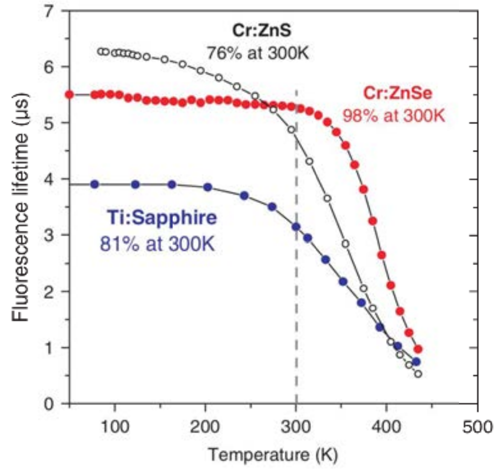
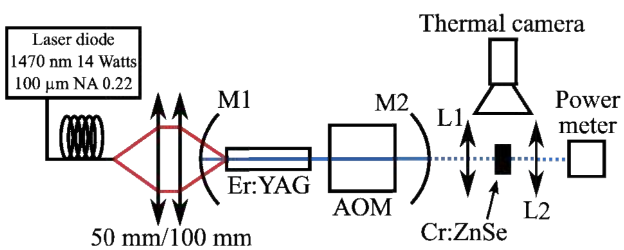


Fig. 10 - Cr:ZnSe upper-state lifetime vs temperature

4.4 Measure of Cr:ZnSe transmissions vs temperature and incident intensity

To acknowledge the previous analysis, we setup an experiment to measure the transmissions of the Cr:ZnSe saturable absorber cristal versus its temperature. The setup is depicted in Fig. 11. From an homemade actively Q-switched Er:YAG cavity, a 1617 nm radiation is focused on a 85% initial transmission Cr:ZnSe. Its temperature is controlled thanks to a Peltier plate. By changing the focal length of the L1 and L2 lenses, and adjusting incident pulse energy, a



mesure can be done for 3 different incident intensities. Results are presentent in Fig. 12.

Fig. 11 - Experimental setup for the measurement of the saturable absorber transmissions. Cr:ZnSe cristal is put on a Peltier plate.

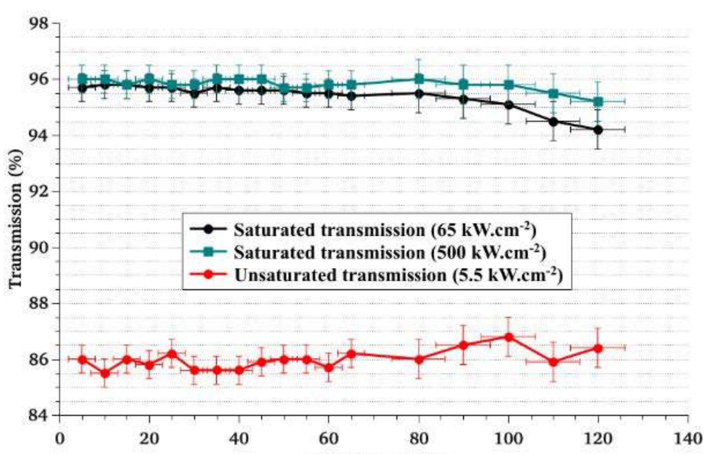


Fig. 12 - Transmissions of Cr:ZnSe cristal versus temperature and incident intensity. Room-temperature saturation intensity of Cr:ZnSe is 15 kW/cm^2.

A drop of saturated transmissions is observed for high temperature, resulting from a raise of the saturation intensity with the temperature. The drop occurs later and is lower when the incident intensity is higher, in accordance to the theory and previous observations. Measurements with temperature up to 220°C are planned.

5. CONCLUSION

In conclusion, we obtained pulse energy up to 220 µJ at 830 Hz from an Er:YAG single crystal fiber at 1617 nm, with pulse duration of 40 ns. This result has been achieved by cooling the saturable absorber temperature down to 25°C.

Without controlling the temperature, we measured operating temperature of the Cr:ZnSe crystal up to 150°C because of residual absorption of pump (for a simple 2 mirrors configuration) and signal (as the transparency can't reach 100% because of excited state absorption). This raise induces a drop (around 60%), unexpected from our simulations, of output performances.

This highlights the need to cool the saturable absorber in order to improve the saturated transmission for better output performances.

Further studies, like ground-state and excited-state spectroscopic measurements or bleaching measurements with temperature over 120°C, can help for a better understanding of mechanisms that occur in a Cr:ZnSe crystal while used as a saturable absorber at 1.6 µm.

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