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# Resonant diode-pumping of Er:YAG single crystal fiber operating at 1617 nm

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## ABSTRACT

We demonstrated laser operation of a Er:YAG single crystal fiber at 1617 nm. Pumped on both sides by a laser diode at 1532 nm, a 600  $\mu\text{m}$  diameter- 60 mm long- single crystal fiber produced an output power of 5.5 W once the wavelength 1617 nm was selected by an intracavity etalon. In Q-switched operation with an acousto-optic modulator, the laser produced an energy of 0.5 mJ at 100 Hz repetition rate with a pulse duration of 28 ns. The Watt level in average power was achieved for a repetition rate of 3 kHz with a pulse duration maintained around 30 ns

**Keywords:** Lasers, Solid-state, Diode-pumped, Q-switched, Erbium.

## 1. INTRODUCTION

Since a few years, resonant pumping of Er:YAG is a laser configuration studied in many laboratories in view of compact eye safe emitters for applications requiring kilometer range propagation in the atmosphere (active imaging or Lidar). The pump sources are either Er:Yb fiber lasers operating at 1532 nm [1,2] or laser diodes emitting at 1470 nm [2-4] or 1532 nm [3,5]. In the majority of configurations, laser emission occurred at 1645 nm. However, a methane absorption line exists at this wavelength in the atmosphere with a typical value of 0.1  $\text{km}^{-1}$  [6] meaning that the transmission is only of 60% over 5 km. One way to increase the range and the efficiency of Er:YAG Lidar systems is to use the 1617 nm emission line which is free of absorption. Even if its emission cross section is higher, laser operation is more difficult to obtain since the population inversion needed to reach the transparency is 14% of the total population (at 300 K) whereas it is only 9% at 1645 nm. Without any selective element in the cavity, the line competition is generally won by the 1645 nm transition. The 1617 nm wavelength was observed in free running only at temperature below 90 K [7], in high loss cavities [8,9] or with injection seeding [10]. With an intracavity etalon, an output power up to 31 W in continuous wave operation [8] and Q-switched pulses with a energy of 30.5 mJ and duration of 20 ns [11] have been demonstrated with a diffraction limited Er:Yb fiber laser as pump source. To our knowledge, direct diode pumping of Er:YAG operating at 1617 nm was only reported with single mode InP laser diode at 1470 nm : the output power was 9 mW for a pump power of 100 mW [9].

In this paper, we demonstrate for the first time that multiwatt output power at 1617 nm is possible with a resonant diode-pumped Er:YAG system. For this purpose, we investigate the potential of single crystal fibers (SCF) for pump confinement and consequently for high inversion population ratio.

Single crystal fibers are long and thin rods with diameter lower than 1 mm and with a barrel surface good enough to guide the pump beam by total internal reflections. In the same time, the signal goes through the single crystal fiber in free space propagation. This concept has been recently successfully implemented for Yb:YAG and Nd:YAG oscillators [12] and showed interesting performance for high gain pulse amplifiers around 1  $\mu\text{m}$  [13, 14]. Pump confinement allows absorption length 5 to 10 times longer than classical diode-pumped crystals: typically of a few centimeters. It is therefore possible to use low doped SCFs. This is a key point for gain media whose laser performance depend strongly on the doping concentration as in Er:YAG [11]. A diameter below 1 mm cannot be easily obtained by classical method (like cutting and polishing of Czokralski boules), therefore, we investigate the micro-pulling down technique which was recently applied to small diameter Er:YAG crystal fibers [15]. After optimization, this technique was able to provide Er:YAG single crystal fiber of optical quality corresponding to the requirements for laser operation [16]. Moreover, the single crystal fibers coming from this process are directly ready to use, with a barrel surface able to guide a highly divergent pump beam.

## 2. EXPERIMENTAL SETUP

In this work, we used small diameter Er:YAG single crystal fibers (600  $\mu\text{m}$  and 800  $\mu\text{m}$ ) in order to maintain a strong confinement of the pump beam, necessary for laser operation at 1617 nm. The doping concentration was chosen at 0.5 % and the length at 60 mm. The experimental setup is shown on the fig.1. The pump light was provided by a fiber-coupled laser diode, with a 400  $\mu\text{m}$  core diameter and a numerical aperture (NA) of 0.22, delivering up to 70 W at 1532 nm. The spectrum was spectrally narrowed by an internal grating, down to 1 nm approximately. The Er:YAG single crystal fiber was both sides pumped in order to reduce the local temperature increase and to distribute the population inversion density all over the gain medium. After collimation by a doublet (focal length of 50 mm), the pump beam was splitted in two parts by a mirror reflecting half of the beam surface. The pump beams were focused by doublets with focal length of 50 mm. The pump beams have a diameter of 400  $\mu\text{m}$  at the focus, located a few millimeters inside the Er:YAG. After free space propagation in the first millimeters of the single-crystal fiber, the pump beam was guided by total internal reflections inside the gain medium.

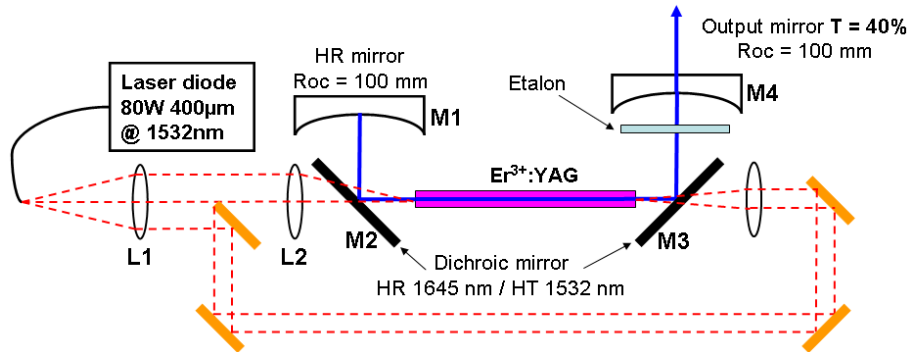


Fig. 1: Experimental setup

Knowing the NA of the pump beams (approximately 0.11 after beam splitting in one direction and 0.22 in the other one), we estimated that the pump beams underwent between 5 and 10 reflections in the single crystal fiber, depending on its diameter. The Er:YAG was anti reflection coated on both ends and put in a copper mount actively cooled at 10°C. The thermal contact between the mount and the fiber was achieved by thermal grease. The cavity consisted in two concave mirrors with a radius of curvature of 100 mm. The first one ( $M_1$ ) was highly reflective for 1617 nm and 1645 nm. The second one ( $M_4$ ) was an output coupler with a transmission of 40% for this wavelength range. The cavity was two times folded by plane dichroic mirrors ( $M_2$  and  $M_3$ ), that are highly reflective at the laser wavelength and that have a transmission of 90 % at 1532 nm. The total optical cavity length was 200 mm.

Before laser operation, the single crystal fiber transmissions were characterized with a probe beam at 1064 nm. Following the absorption spectrum of Er:YAG [15], the crystal fiber was free of absorption at this wavelength. With a waist diameter of 300  $\mu\text{m}$ , we found a transmission of 86 % (600  $\mu\text{m}$  diameter) and 92 % (800  $\mu\text{m}$  diameter). The output profile of the probe beam was monitored by a CCD camera and was found to be very close to the input profile of the laser probe. The depolarization losses were measured to be less than 4 %. The probe was then focused on a spot diameter of 20  $\mu\text{m}$  corresponding to a Rayleigh range in the same order than the pump one. The transmission was then measured at 47 % (600  $\mu\text{m}$  diameter) and 57 % (800  $\mu\text{m}$  diameter). Following the number of reflections, we estimated that the barrel surface had a reflectivity between 90 % and 95 %. Compared to 800  $\mu\text{m}$  diameter SCF, the transmission and the barrel surface of the 600  $\mu\text{m}$  diameter SCF were not as good, because the growing process was less optimized for this fiber diameter.

## 3. RESULTS

Without any selective element in the cavity, the laser operated at 1645 nm. For both diameters of SCFs, we obtained similar output powers, close to 8 W for 65 W of incident pump power (sum of the two pump beams). In order to select 1617 nm emission, we inserted a 50  $\mu\text{m}$  thick BK7 etalon in the cavity close to the output mirror. Fig.2 reports the laser performance obtained at 1617 nm after wavelength selection by the rotation of the etalon. Despite more losses in the 600  $\mu\text{m}$  diameter single crystal fiber, the output power reached 5.5 W whereas it was only 3 W for the 800  $\mu\text{m}$  SCF. The threshold was also much higher with the 800  $\mu\text{m}$  SCF. These curves demonstrate the interest to confine the pump beam via a small diameter single crystal fiber for quasi-three level laser operation.

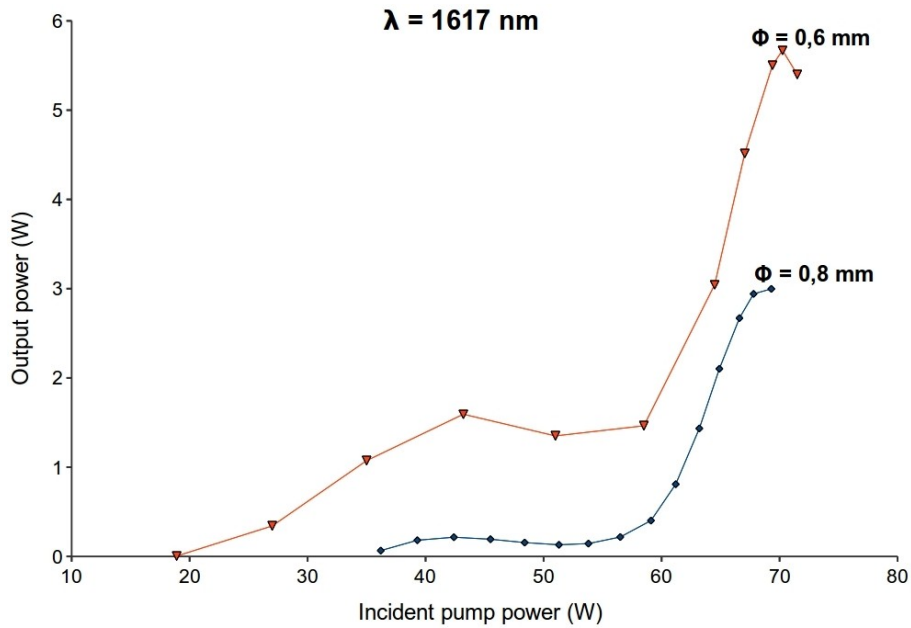


Fig. 2: CW output power at 1617 nm versus incident pump power for tow diameter of SCFs (0.8 mm and 0.6 mm).

For the 600  $\mu\text{m}$  SCF, we tested different output couplers and found that the 40 % transmission was the optimum one. Laser oscillation was obtained for an output mirror transmission up to 65 % showing that the double pass small signal gain in the Er:YAG single crystal fiber was higher than 3.9 (taking the passive losses into account).

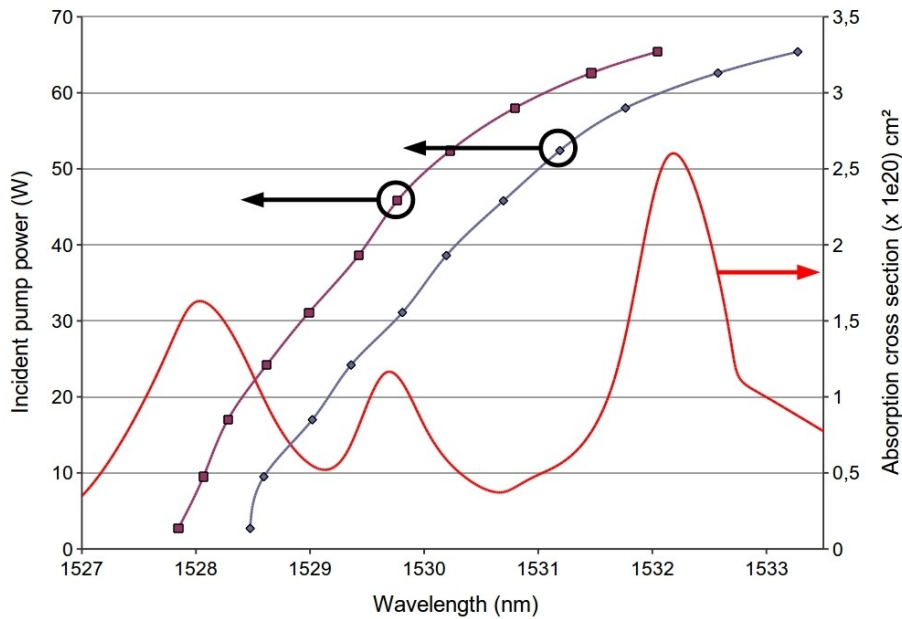


Fig. 3: Lines with squares : pump diode spectrum edges (at  $1/e^2$ ) for different pump powers. Solid line : absorption spectrum of Er:YAG (from [17]).

Both efficiency curves present a hole between 40 W and 55 W of incident pump power. This can be understood by the spectral shift of the laser diode presented on the fig.3. When the pump power increased, the spectrum broadened and shifted towards long wavelengths. Fig.3 gives also the absorption spectrum of Er:YAG around 1532 nm. It shows that between 40 W and 55 W, the laser diode spectrum corresponds to a hole between two peaks of absorption. As the

absorption was lower, the overlap between the pumps and the signal was worse, despite the pump guiding effect of the single crystal fiber. This may explain the decrease in output power.

We also investigated the spatial profile of the output beam. For the 800  $\mu\text{m}$  diameter SCF, we measured a  $M^2$  factor very close to 1 at a pump power of 40 W and equal to 1.8 at a pump power of 65 W. At this pump power level, the beam profile was found to be even better with the 600  $\mu\text{m}$  SCF (see inset in Fig.4), certainly due to the spatial filtering imposed by the small diameter. An evolution of the output beam versus the pump power is shown on Fig.4 for the 600  $\mu\text{m}$  SCF in horizontal and vertical directions. It shows that the beam profile was not modified up to 55 W of incident pump power. A strong decrease induced by thermal lens effect was recorded for higher pump powers. This effect combined with temperature increase explains the saturation of the efficiency curve around 65 W of incident pump power.

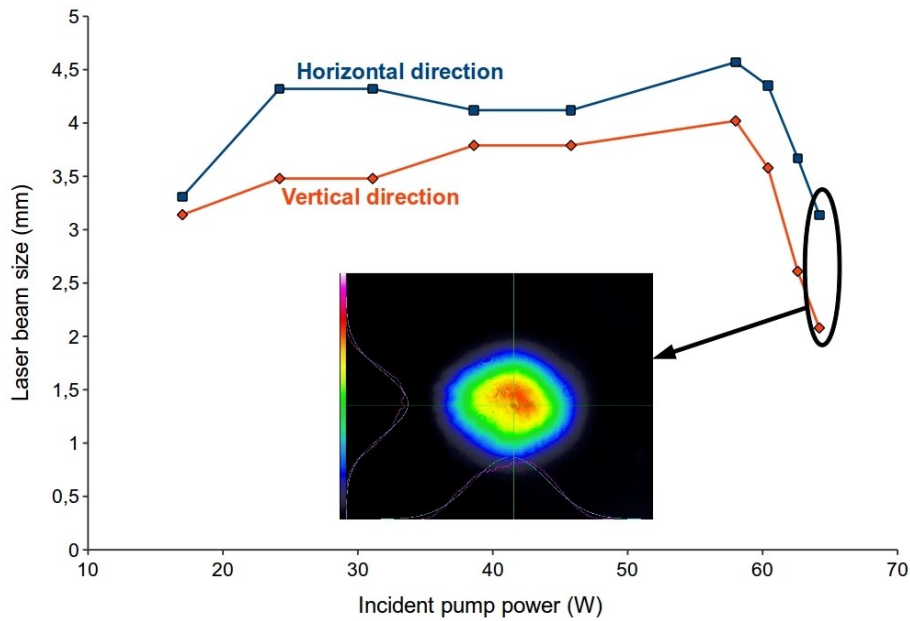


Fig. 4: The beam size are measured at  $1/e^2$  on horizontal and vertical directions for the 600  $\mu\text{m}$  diameter SCF. Inset : beam profile at maximum pump power for the 600  $\mu\text{m}$  diameter SCF.

Q-switched operation was carried out with the 600  $\mu\text{m}$  diameter SCF. We introduced an acousto-optic modulator between  $M_1$  and  $M_2$ . We also increased the output coupling up to 50 % to avoid damage on the intracavity optics. The acousto-optic modulator brought 14% (double pass) additional losses because of non optimized AR coatings reducing the output power to only 2 W in continuous wave. In Q-switched operation we achieved a maximum energy of 0.5 mJ at 100 Hz (Fig.5) with a pulse duration of 28 ns at 1617 nm. The pulse duration stood around 30 ns up to a repetition rate of 3 kHz and nextly increased almost linearly to 110 ns at 20 kHz. To our knowledge, 28 ns is the shortest pulse duration ever produced by a directly diode-pumped Q-switched Er :YAG laser since the previous values are 58 ns [2] and 70 ns [5]. This can be attributed to the high gain available with the pump confinement offered by the 600  $\mu\text{m}$  diameter SCF.

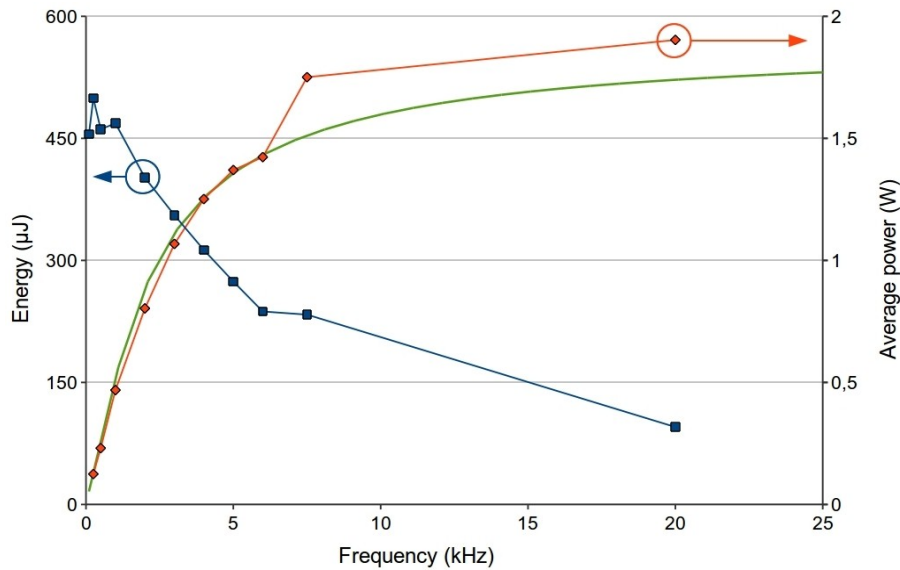


Fig. 5: Energy (left) and average power (right) versus pulse repetition rate in Q-switched operation (dots : experiment, solid line : simulation).

The Q-switched performance was recorded by starting at high repetition rate. When we decreased the frequency at 7 kHz, we observed parasitic oscillations attributed to insufficient losses introduced by the acousto-optic modulator. We avoided those oscillations by increasing the losses in the cavity with a slight misalignment of the mirror  $M_4$ . This explains the fall of average power recorded around 7 kHz (Fig.5). Below this repetition rate, the average power decreased rapidly (Fig.5). Assuming that the decay from the upper level is proportional to the population density, we found an effective lifetime of 270  $\mu\text{s}$  (fit on Fig.5) which is very far from the fluorescence lifetime of  $\text{Er}^{3+}$  in YAG given at 6.2 ms [15] and smaller than values reported (2.3 ms [4] or 2 ms [2]). This very small value may be due to high pump power density in our setup (estimated to 26  $\text{kW}/\text{cm}^2$  at the focus) whereas it is only of a few  $\text{kW}/\text{cm}^2$  in [2] and [4]. Reduction of effective lifetime can be attributed to up-conversion, and may also depend on stimulated emission at the pump wavelength and on parasitic laser effects. Numerical simulations have to be carried out to estimate the influence of those different effects.

In conclusion we have demonstrated that the single crystal fiber geometry is well adapted for direct resonant diode pumping of Er:YAG with laser action on a quasi-three level transition at 1617 nm having a strong population in the lower level. Compared to the previous state of the art, the output power of 5.5 W obtained in this work is more than 600 times higher than previously reported for a resonant diode pumped Er:YAG laser emitting at 1617 nm [9]. We reported also the first results in Q-switched operation at 1617 nm for a diode-pumped Er:YAG laser. Despite a lot of passive losses induced by non-optimized components (namely the single crystal fiber, the acousto-optic modulator and the etalon) the performance obtained in pulse operation combined short pulse duration (30 ns) with a significant energy (300  $\mu\text{J}$  to 500  $\mu\text{J}$ ) and an average power at the watt level. Those values may address direct detection LiDAR's requirements for example. Apart from reduction of passive losses, other possibilities may improve the wall plug efficiency of this laser: a lower doping concentration should reduce up-conversion losses. A pumping at 1470 nm could improve the stored energy by avoiding stimulated emission at the pump wavelength. Finally, the Er:YAG single crystal fibers have the potential for simple, compact and efficient eye safe lasers at 1617 nm.

#### 4. ACKNOWLEDGEMENT

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