# Ultra High Brightness Laser Diode Modules around 1.5 µm for Highly Efficient Resonant Pumping

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## 1. INTRODUCTION

Interest in eye-safe lasers rose in the last few years high power lasers for ranging and detection applications, especially gas detection in air over long distances. For those tasks, long-range propagation in free space with potential for human exposure, both high eye safety and low absorption rates are crucial. There are only few types of lasers that can be used: One choice are OPO lasers, which are large and very sensitive, but can be adjusted to a suitable wavelength. Fiber lasers, another choice, don't allow for wavelength adjustment or high power with good beam parameters. Erbium doped solid state lasers are a much better candidate. For erbium-doped materials usually lasing at 2.9 µm, it is very difficult to achieve high pump efficiencies from the 4I15/2 → 4I11/2 transition due to competing up conversion processes. The resonant pumping process is characterized by high quantum efficiency, which can be achieved at several narrow pump wavelengths around 1.5 µm. A quasi-two level laser process involving the 4I13/2 → 4I15/2 levels lead to laser radiation at 1617 nm or 1645 nm. These two transitions are pumped with the same wavelength and compete with each other. For wavelength selection an etalon or volume Bragg grating can be used, exploitation of the gain cross-section is another option. The gain-cross section progresses differently for both wavelengths whereby 1617 nm becomes the dominant wavelength at an inversion parameter of about 0.3 [1]. By varying the losses within the resonator the lasing wavelength can be adjusted, which allows detection of $CO_2$ at 1617 nm and methane (CH4) at 1645 nm with the same setup within a lidar system. This laser process is only affected by up-conversion and ESA, which can be observed by green light emission of the crystal. This requires the erbium concentration to be very low (below 1 at%). Another benefit of Er:YAG is the long lifetime of the upper level which is about 7 ms. Usually, pulsed pump sources are used for q-switch operation. Due to the long lifetime Er:YAG is suitable for cw-pumping to achieve high energy in q-switched operation. As early as 1972, K.White and S.Schleusener suggested Er:YAG lasers at 1.6 µm for methane detection [2], however resonant pumping was not yet possible with GaAs-based lasers. With the development of high power InP-based laser diodes around 1.5 µm, a new way for pumping erbium lasers has now become available.

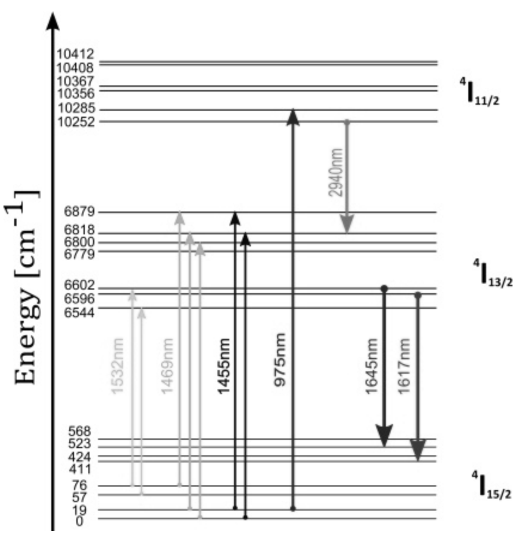



**Figure 1:** Laser levels of Er:YAG laser with lasing wavelengths at 1.6 µm and 2.9 µm

## 2. EXPERIMENT

### *2.1 Narrow bandwidth diodes lasers as pump source*

A very stable narrow bandwidth pump source is necessary to achieve high pump efficiencies in resonantly pumped lasers. Typical laser diodes have a FWHM of more than 5 nm, and the center wavelength shifts with pump current and diode temperature. This is sufficient for most solid state lasers, but the narrow pump levels of the resonantly pumped Er:YAG lasers require a more narrow pump source, since all the power not deposited in the pump levels is lost through up-conversion, exited state absorption and heat. To further increase the pump efficiency it is also possible to pump with 1532 nm instead of 1455 nm to take advantage of the higher quantum efficiency, but the 1532 nm band is narrower and thus a pump source with a very stable center wavelength and narrow bandwidth is needed for effective pumping. In fact, Er:YAG lasers can be pumped simultaneously by all five possible pump wavelength to achieve high power laser output at 1.6 µm.

The ultra-high brightness diode laser modules from DirectPhotonics Industries GmbH (DPI) use a novel architecture to achieve narrow bandwidth for resonantly pumped Er:YAG lasers. 12 broad-area single emitter laser diodes are stacked in a staircase arrangement. The laser emission from the lasers then is optically stacked via a slow axis collimator (SAC), consisting of a monolithic copper block with 12 curved facets collimating and redirecting all beamlets. The fast axis collimators are then used to actively align the beams through the system to achieve optimum brightness. Polarization combining increases the brightness further, allowing to couple 24 diodes into a 100 µm fiber. The beam profile is only limited by the size of the emitting area of the diodes. The diode material used for the experiments described here had a 100 µm emitter width, allowing coupling into a 100 µm fiber, 0.15 NA, equating a beam parameter product of 7.5 mm·mrad.[3]

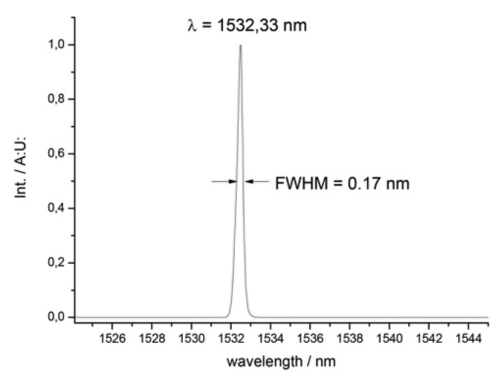
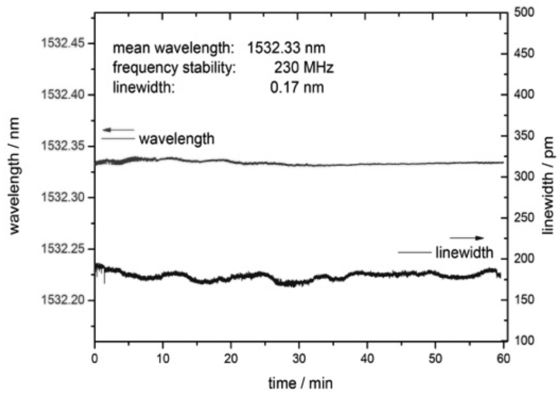



**Figure 2:** Spectrum of 20 W DPI DirectPump module at 1532.33 nm

Wavelength stabilization is achieved with a single volume Bragg grating (VBG) located behind the SAC, which provides an external feedback to all single emitter lasers in one module by coupling a small percentage of the laser beams back into the diodes. This locks all emitters to one specific wavelength with a narrow bandwidth of 0.2 nm. For the experiments we used a DPI DirectPump P-1532-20-200-0.22-LEF laser module. That laser emitted at a wavelength of 1532.3 nm and FWHM of 0.17 nm. Long-term measurements showed a frequency stability of about 230 MHz over one hour. The VBG wavelength stabilization allows to use a standard chiller without temperature stabilization, and the wavelength is nearly independent of current changes and measured to be only 0.01 nm / W.



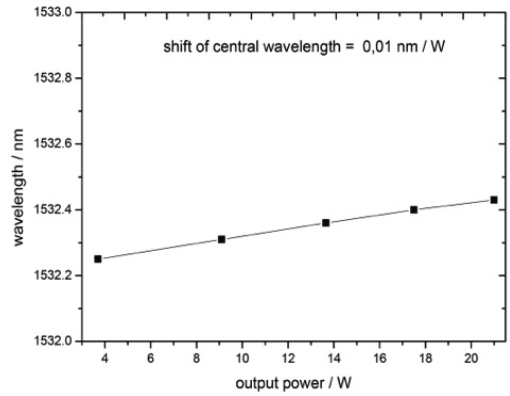




**Figure 3:** Long term stability of DPI DirectPump was observed with 230 MHz (left side) and wavelength stability with increasing output power (right side) with only 0.01 nm / W

### *2.2 Er:YAG lasers operating at 1645 nm*

The Er: YAG laser presented here is designed to be used within a space borne lidar system for methane detection, requiring it to be as compact as possible while generating highly stable high power output at 1645.55 nm. For that purpose we set up a cw resonator in an L-shaped cavity, consisting of a 45° input coupler and a curved HR-mirror in the long arm and a variety of flat output couplers. This design allows to easily introduce wavelength stabilizing elements (e.g. etalons) and a Pockels cell for q-switching.

Using the DPI narrow bandwidth laser as pump source we were able to observe a wavelength stability of 113 MHz over 300 s at a center wavelength of 1645.55 nm. The output power was measured to be 2.5 W at an absorbed pump power of only 9 W, which is an optical efficiency of 28%. The absorption efficiency of pump source was measured to 96% due to the narrow bandwidth of the diode laser module, yielding a higher wall plug efficiency than possible with fiber laser pumping. The slope efficiency of the Er:YAG laser is in the same range as fiber laser pumped systems.

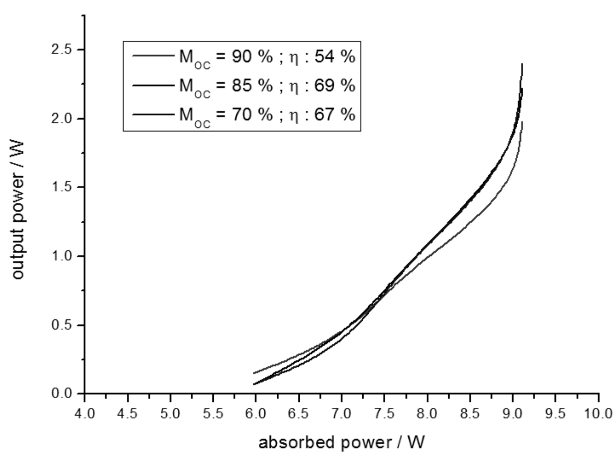



**Figure 4:** Efficiency for different output couplers

This is very promising for space-borne lidar applications, but in the cw configuration only the presence of methane and its concentration can be detected. The long upper level life time of approximately 7 ms makes Er:YAG laser very suitable for q-switched mode operation with cw pump sources. We used an Alphalas LiNbO3 Pockels cell in Brewster cut for q-switching, placed in in front of the curved mirror (see Fig. 5 left). A maximum energy of 6.2 mJ and a pulse width of 60 ns was observed (see Fig. 5 right). The repetition rate can be set to 150 Hz without any changes in the resulting pulse width.

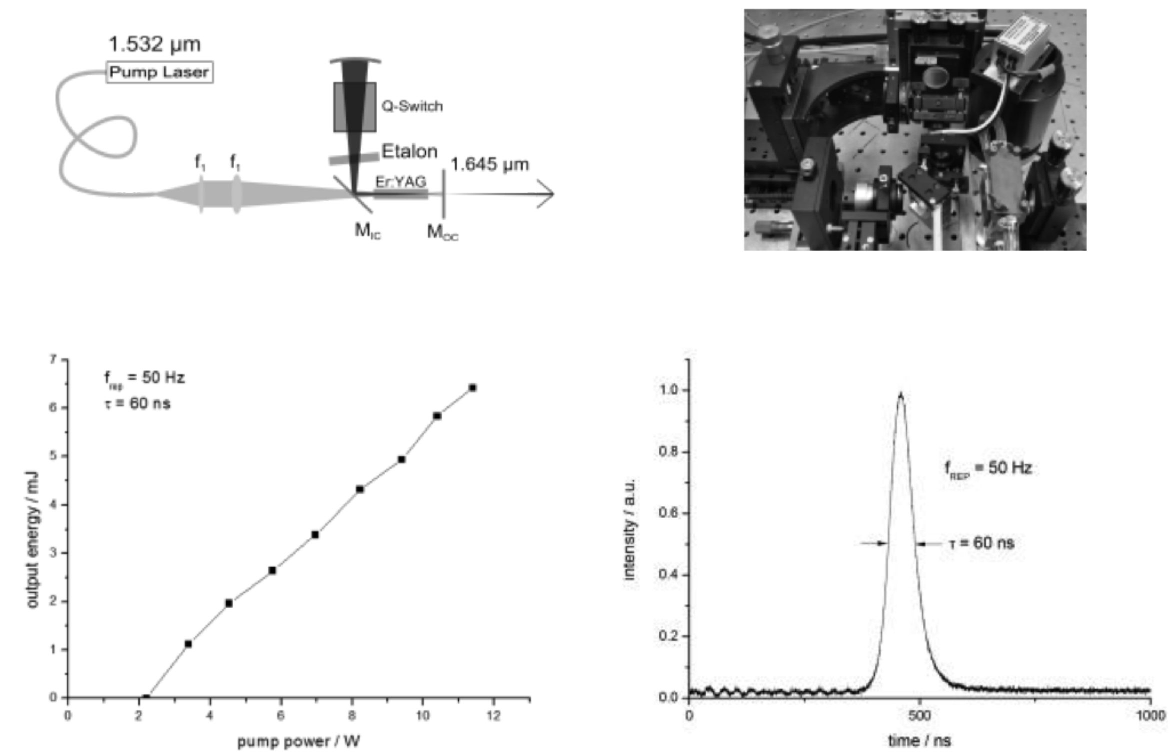



**Figure 5:** Left: setup of the L-shaped resonator for cw and q-switched operation
Right: resulting output energy in q-switched mode using a Pockels cell.

This setup is very close to the specifications needed for methane detection and LIDAR applications. Methane shows strong absorption lines at 6077.1 $cm^{-1}$ (1645.52 nm) and 6078.4 $cm^{-1}$ (1645.17 nm) [4]. To tune the wavelength to one of these lines an etalon was inserted into the cavity. Rotating the etalon allowed us to tune the laser wavelength between 6077.1 $cm^{-1}$ and 6078.6 $cm^{-1}$, and even as far as 6184.1 $cm^{-1}$ (1617.08 nm), which coincides with strong $CO_2$ absorption lines. Using a 3 mm etalon increased the linewidth to 0.01 $cm^{-1}$ (0.002 nm) and the frequency stability increased to 40 MHz. Methane absorption was measured successfully between 6078.44 $cm^{-1}$ and 6078.47 $cm^{-1}$ at pressure levels between 1 mbar and 300 mbar (total absorption). The beam quality was measured to be $M^2$ = 1.2.

## 3. CONCLUSION

We demonstrated Er:YAG lasers with high beam quality in different resonator configuration. An absorption efficiency of 96% was achieved. By resonant pumping the 0.5 at% Er:YAG lasers a slope efficiency of over 70 % and optical to optical efficiency of more than 20% were demonstrated. The high output power of 2.5 W at 1645 nm and a linewidth of less than 2 pm makes this system a very good choice for methane detection. In q-switched mode, a pulse width of 60 ns and a pulse energy of 6.6 mJ was demonstrated, which is necessary for LIDAR applications. By implementing intra cavity etalons, wavelength tuning was demonstrated switching rapidly between the off and on wavelengths for $CO_2$ and methane absorption lines, which makes it suitable for use in DIAL systems. Feasibility of a DIAL system for methane detection was successfully demonstrated at 6078.46 $cm^{-1}$. The long-term frequency stability was measured to be 40 MHz, due to the very stable narrow bandwidth diode laser used as pump source.

Wavelength stabilized diode laser module with high brightness are a good pump source for resonant pumping: The absorption efficiency very high, and the wavelength stability leads to highly stable solid state lasers. Another benefit is the free choice of wavelength of the diodes used within the DPI diode laser modules, allowing to use pump modules with different wavelengths, leading to very high power resonantly pumped Er:YAG lasers.

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