Efficient 1.5 W CW and 9 mJ quasi-CW TEM_{00} mode operation of a compact diode-laser-pumped 2.94-µm Er:YAG laser

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ABSTRACT

An efficient, compact diode-laser-pumped 2.94µm Er:YAG laser operating at 1.5 W continuous output power in a TEM_{00} beam with $M^2<1.2$ has demonstrated pulsed operation in the quasi-cw regime with energies up to 9 mJ. Power scaling and output beam fiber-coupling at 85% efficiency in a hermetic package will be described.

Keywords: CW lasers, erbium, Er:YAG, diode-pumped laser, solid-state lasers, pulsed lasers, infrared lasers.

INTRODUCTION

We have developed the first commercially available diode-laser-pumped continuously operating (CW) 1.5 W, 2.94µm Er:YAG laser (http://www.sheaumann.com/products-MIRW.html) in the end-pumped microlaser chip configuration first demonstrated by Chen et al. [1] and extended to other Er^{3+}-doped garnets by Dinerman and Moulton [2]. The advent of higher power and brightness diode pump laser sources that are long lived is one of the primary reasons why this technology is now commercially viable.

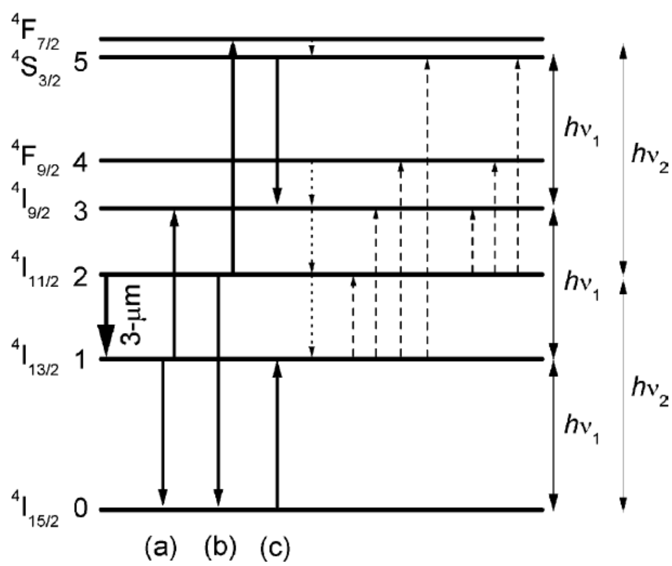


Figure 1. A simplified energy level diagram for Er:YAG showing the pump absorption and laser transitions. Cooperative upconversion between pairs of Er^{3+} ions provides greater than unity quantum efficiency and overcomes bottlenecking in the $^4I_{13/2}$ lower laser level. This diagram was reproduced from Georgescu and Toma [4].

The need for a high brightness pumping source lies in the energy level dynamics of laser. Referring to the energy level diagram (Figure 1) the 6.4 ms lifetime of the lower laser level, $^4I_{13/2}$, is much longer than the 0.1 ms lifetime of the upper laser level, $^4I_{11/2}$, which would lead to self-saturation under normal circumstances. However, at high Er^{3+} concentrations under intense pumping, cooperative upconversion between neighboring Er^{3+} ions depletes the $^4I_{13/2}$ level of one ion while simultaneously providing a pumping path to the upper laser level via the $^4I_{9/2}$ energy level as indicated in column (a) of Figure 1. This effect prevents self-termination of the lasing while at the same time providing almost two photons at the laser wavelength for every absorbed pump photon population thereby providing greater than unity quantum efficiency [1, 3, 4]. Upconversion from the $^4I_{11/2}$ energy level (column (b) in Figure 1) and cross-relaxation from the $^4S_{3/2}$ energy level (column (c) in Figure 1) are also known to play a significant role in the 2.94µm Er:YAG laser dynamics [4].

Flashlamp pumped 2.94µm Er:YAG and Er:YSGG lasers are used extensively in hard and soft tissue dental procedures and there has been recent interest in the use of lower energy quasi-cw diode-laser-pumped devices for micro-surgical applications [5]. In this work we describe the performance of a 1.0 W cw 2.94µm Er:YAG laser (Sheaumann's MIR-Pac laser) and its quasi-cw characteristics. In its current form this device has potential use in soft tissue micro-surgical applications; other application areas include spectroscopy when used as an OPO pumping source.

CW LASER PERFORMANCE

In the cw operating mode the MIR-Pac laser is specified for operation at maximum 1.0 W of output power (see Figure 2) in an M^2<1.2, TEM_{00} mode beam (see Figure 3) with a typical beam divergence of 17 mrad. Recent improvements have resulted in the generation of up 1.5 W output power limited by the onset of thermal rollover, which we believe is related to thermal lensing in the microlaser chip and work is in progress on the use of a short laser resonator designed to independently control the mode size and resonator stability to allow for efficient operation at higher output powers.

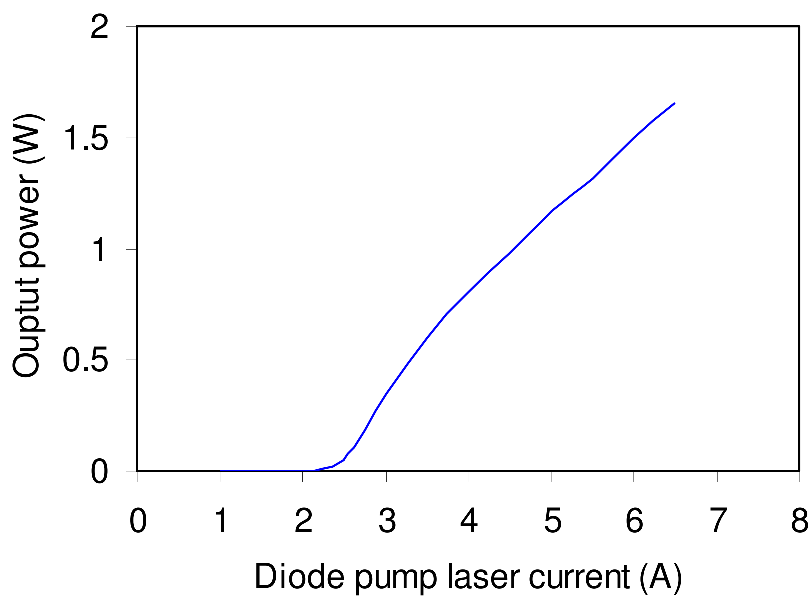


Figure 2. CW output power of a 2.94-µm MIR-Pac laser versus the diode pump laser drive current.

QUASI-CW LASER PERFORMANCE

The 2.94-µm Er:YAG laser is optically pumped using a diode laser that may be operated continuously, or pulsed, by using the appropriate drive current waveform. By driving the diode laser with a rectangular current pulse with rise times <10 µs the corresponding optical pump pulse can efficiently create a population inversion that exceeds the lasing threshold. Nominally rectangular laser pulses with durations from <0.1 ms up to a large fraction of a second can be generated and this is referred to as quasi-cw operation because the pulse durations are long enough that the laser output attains a steady-state. In this mode of operation the laser may be operated at peak powers proportionally higher than the laser average power operating limit by a factor that is the inverse of the duty cycle of the quasi-cw laser pulse train. The current implementation is limited by the diode pump laser maximum peak power of approximately 10 W, which will be increased in the next generation device.

Meister et al. [5] demonstrated the generation of 15.7 mJ in 2.5 ms pulses from a quasi-cw diode-laser-pumped Er:YSGG laser designed for use in soft tissue microsurgical applications, which compares favorably to our 6 mJ in 2.5 ms data presented below. Meister et al. also presented a comprehensive review of other quasi-cw diode-laser-pumped 3-micron Er-lasers that are able to generate 30 mJ energies, but are not amenable to optimized for efficient operation at lower pulse energies nor are they cost effective because of their use of stacked arrays diode laser bars.

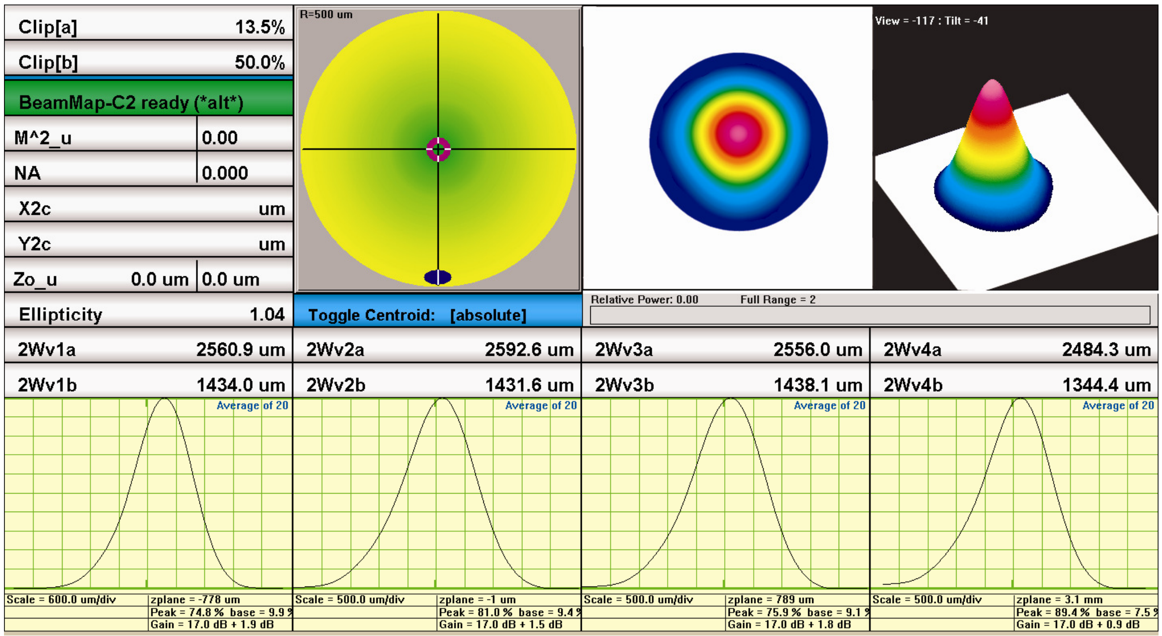


Figure 3. Typical TEM_{00} output beam data for the 2.94-µm MIR-Pac laser.

Figure 4 shows a typical quasi-cw Er:YAG laser pulse generated by pumping with a 0.5 ms diode laser pulse at a 1000 Hz repetition rate. A series of gain-switched pulses are emitted at the onset of lasing and transition into the well known damped relaxation oscillation (see Figure 5) condition followed by oscillation free quasi-cw laser operation that terminates immediately after the pump pulse is extinguished. There is also a measurable, 6 µs, build up time delay from the start of the pump pulse to the lasing threshold. The build up time delay will shorten for higher peak pump powers and for the generation of millisecond duration pulses it is of little significance. The 100 µs transition to the stable quasi-cw is more significant when generating sub-millisecond pulses.

The relaxation oscillation damping time, τ_0, of an ideal four level laser [6] is given by

$$\tau_0 = \frac{2\tau\left(1 - N_{th}/N_t\right)}{W_p/W_{p,th}}$$

where the characteristic lifetime of the upper laser level, τ, is modified by the ratio of the population inversion density at threshold to the total number of active ion sites in the pumped region of the gain medium, N_{th}/N_t, and the number of times the optical pumping rate exceeds the lasing threshold, $W_p/W_{p,th}$. It is clear that pumping harder shortens the relaxation oscillation damping time and this basic fact still applies to the 2.94-µm Er:YAG laser even though its energy level dynamics are much more complex than those of the ideal four level laser.

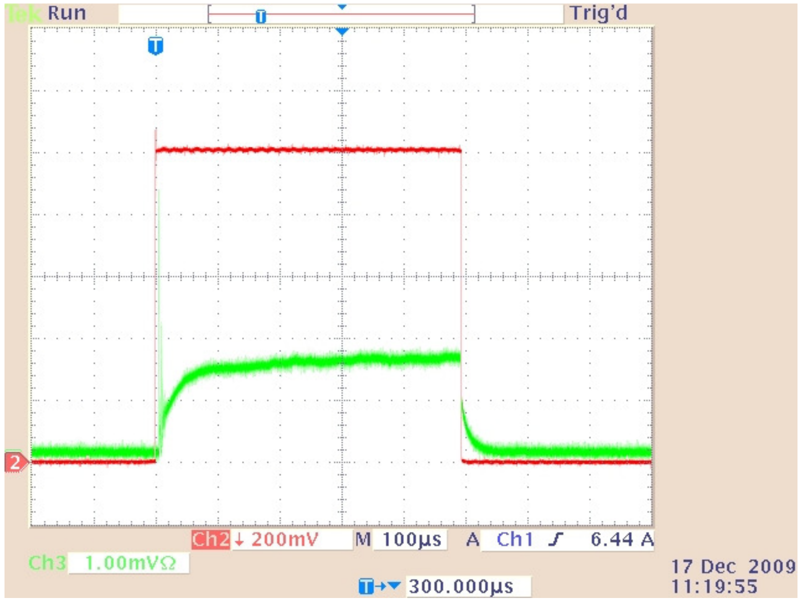


Figure 4. The quasi-cw laser output (lower trace) and drive current waveform (upper trace) for a 0.5-ms duration, 10 A current pulse at a 1000 Hz repetition rate.

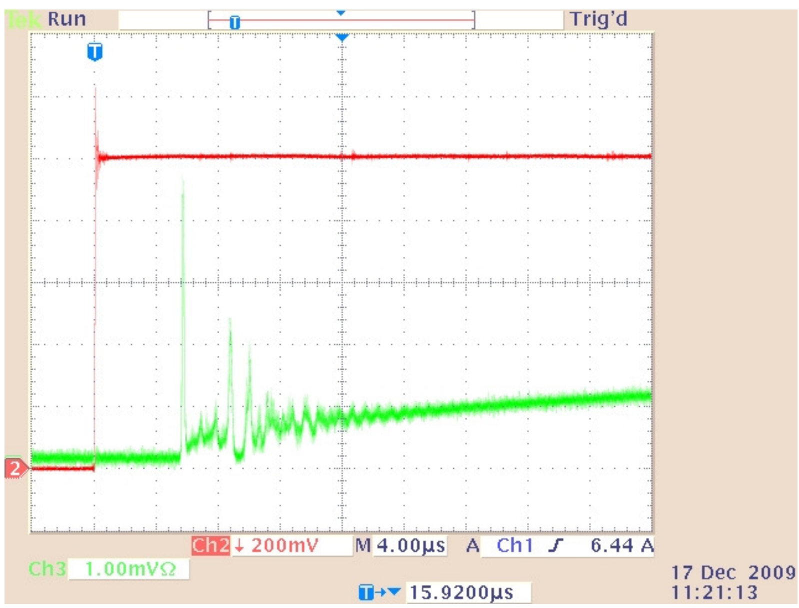


Figure 5. The quasi-cw laser output (lower trace) and drive current waveform (upper trace) showing the relaxation oscillations at the beginning of the pulse shown in Figure 4.

Pumping the Er:YAG laser close to, but below, its lasing threshold prior to the main pumping pulse shortens the relaxation damping time and almost eliminates the build up time delay (see Figure 6). The ideal pulsed drive current for quasi-cw operation of the laser consists of a continuous bias current set to 80% to 90% of the continuous lasing threshold value (typically 2 A) with a larger pulsed drive current. The peak drive current may be as high as the 10 A maximum permissible drive current of the diode pump laser, with the additional constraint that the duty cycle corrected average 2.94-µm laser output power does not exceed the specified maximum operating power of the device.

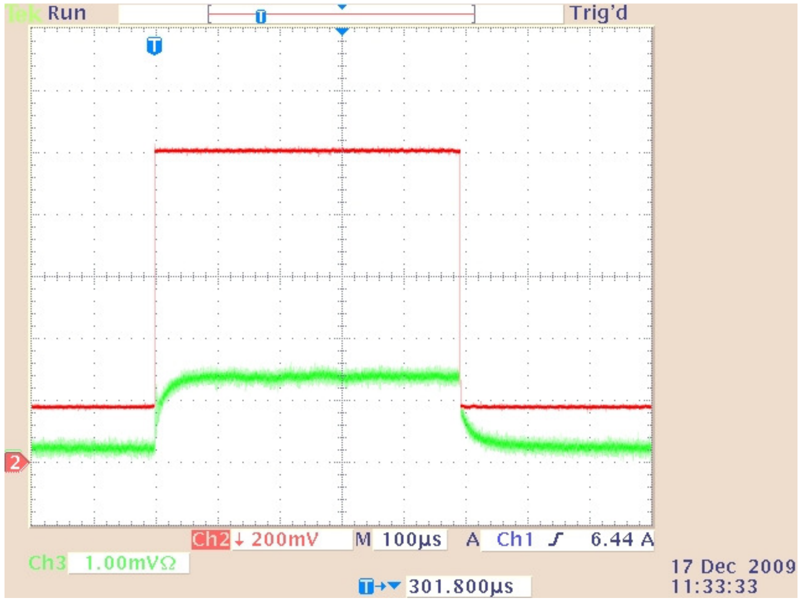


Figure 6. The quasi-cw laser output (lower trace) and drive current waveform (upper trace) for a 1.0-ms duration, 8.2 A current pulse superimposed on a 1.8 A continuous bias current at a 1000 Hz repetition rate.

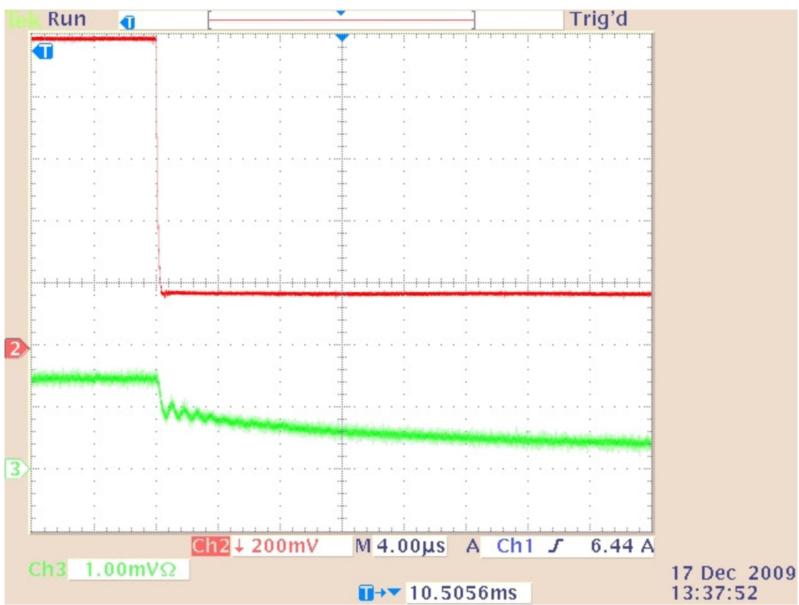


Figure 7. The quasi-cw laser output (lower trace) and drive current waveform (upper trace) showing the relaxation oscillation decay at the end of the laser pulse shown in Figure 6.

At the end of the optical pump pulse most quasi-cw lasers turn off with a monotonic decay in intensity and we observed this behavior when the diode pump laser was turned completely off at the end of the pumping pulse. Yet, when the diode pump laser was operated continuously just below the Er:YAG laser threshold between the pumping pulses we observed a series of decaying relaxation oscillations (see Figure 7) at the end of the Er:YAG laser pulse. We believe these oscillations are a unique feature of the laser dynamic response that arise because of the continued and slowly decaying optical pumping of the upper laser level via the upconversion pathway providing phase delayed feedback.

The pulsed peak power capability of the Er:YAG laser is ultimately limited by the same thermal fracture mechanism as in continuous operation, which for the current product is specified at 1 W and recent device improvements allow operation up to 1.5 W (see Figure 1). The corresponding recommended peak power limit for quasi-continuous operation at a duty cycle of 10%, i.e. 1 ms pulses at a repetition rate of 100 Hz, would therefore be >10 W. In practice, the pump diode laser in the standard 2.94-µm MIR-Pac Er:YAG laser product is limited to a maximum drive current of 10 A, which typically corresponds to peak powers up to 2.5 W.

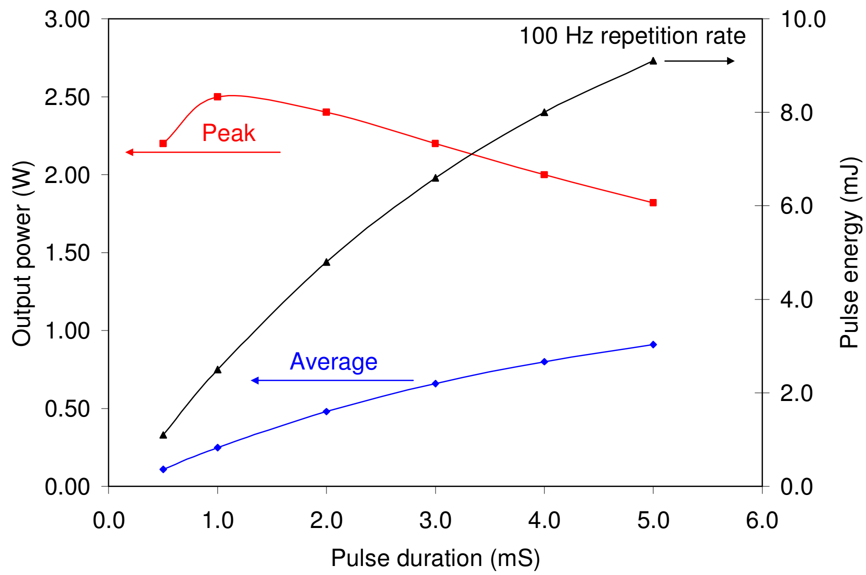


Figure 8. The quasi-cw laser performance at a fixed pulse repetition rate of 100 Hz for 8.2 A drive current pulses superimposed on a 1.8 A continuous bias current.

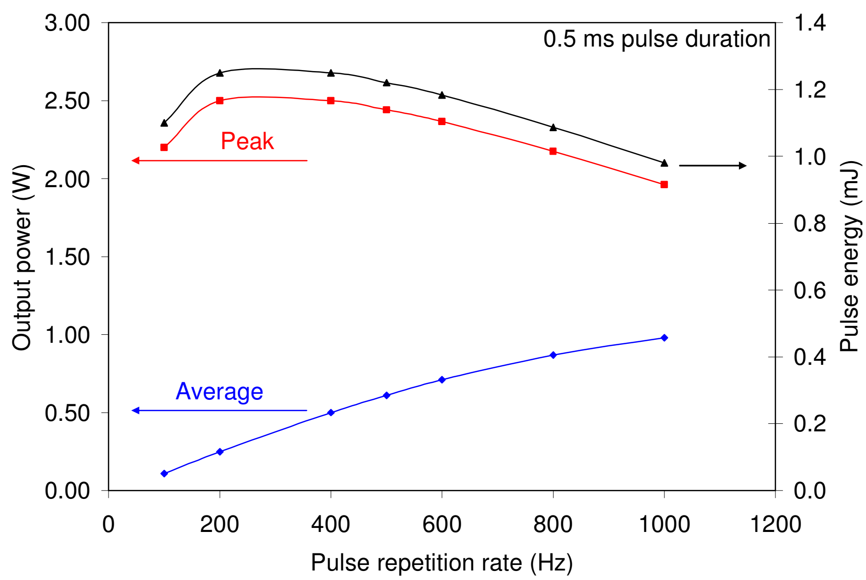


Figure 9. The quasi-cw laser performance at a pulse duration of 0.5 ms for 8.2 A drive current pulses superimposed on a 1.8 A continuous bias current.

The data in Figures 8 and 9 demonstrate the generation of up to 2.5 W peak powers in quasi-cw operation at the maximum drive current limit when generating millisecond regime pulses at pulse repetition rates. The maximum pulse energies of 9 mJ were generated for 5 ms, pulses at 1.8 W of peak power. The average power limit is only reached at duty cycles of approximately 50% and pulse peak powers as high as 2 W; with corresponding pulse energies of 1 mJ at 1 kHz.

When operating at low duty cycles with long intervals between laser pulses transient thermal lensing results in undesirable spatial mode modulation. Operating the Er:YAG laser close to threshold, but not lasing, between laser pulses helps to prevent this problem by introducing a significant fraction of the thermal lens experienced under lasing conditions. This problem can be seen in Figure 10, where the rising edge of the pulse walks through a series of relaxation oscillation events indicative of multiple spatial mode evolution and Figure 11 shows the elimination of the problem.

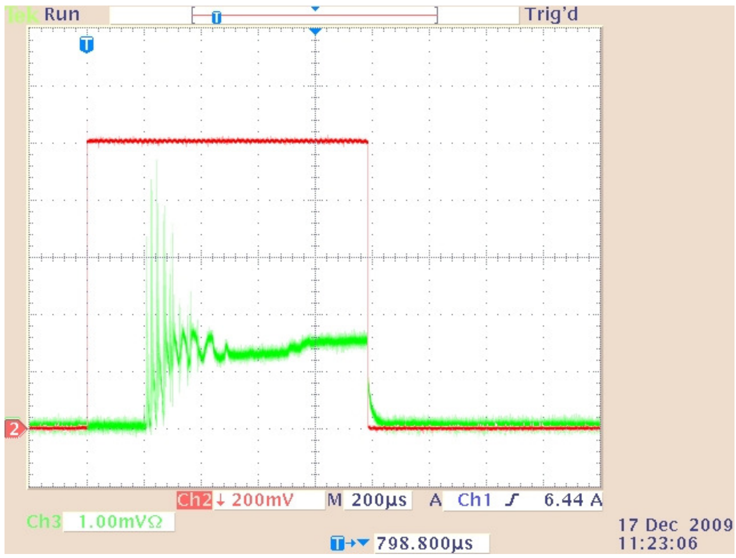


Figure 10. The quasi-cw laser output (lower trace) and drive current waveform (upper trace) for 0.5-ms duration. 10 A drive current pulse.

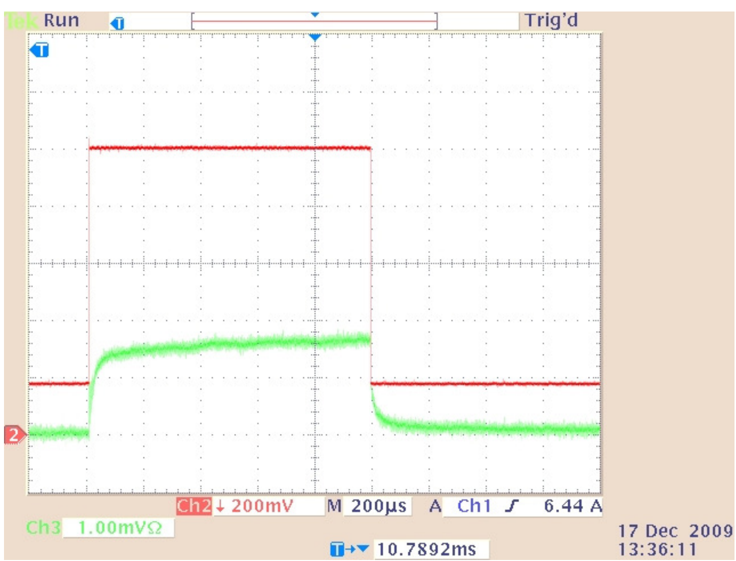
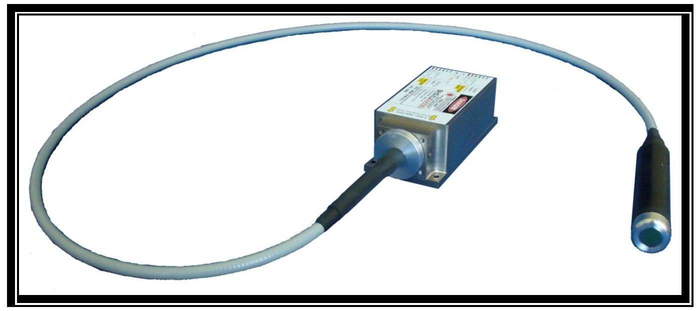


Figure 11. The quasi-cw laser output (lower trace) and drive current waveform (upper trace) for 0.5-ms duration. 8.2 A drive current pulse superimposed on a 1.8 A continuous bias current.

The data shown above was from an Er:YAG laser in a hermetically sealed windowed package. (See Figure 12)
We have recently tested fiber-coupled versions of the laser package with 0.22 NA ZBLAN (IRphotonics) fibers ranging in core diameter from 150 µm to 450 µm. Fiber-coupled output powers of 1.1 W were obtained for 1.3 W of power incident on the input face of 1.5-m long fibers of all cores sizes. After accounting for the output fiber face Fresnel loss the power coupling efficiency was estimated to be >90%. See Figure 13

Figure 12: Direct Beam Output

Figure 13: Fiber Coupled Version



SUMMARY

We have developed an efficient diode-laser-pumped 1.5 W, cw 2.94µm Er:YAG laser with a TEM_{00} output beam in a hermetically sealed windowed package with a fiber-coupled output beam delivery option providing 1.1 W from 150 µm to 450 µm core diameter, 0.22 NA ZBLAN (IRphotonics) optical fibers. This laser has been operated in the quasi-cw mode to generate pulse energies as high as 10 mJ in a 5 ms pulse at a 100 Hz repetition rate. Alternatively, 1 mJ pulses can be generated at repetition rates from a single-shot to 1 kHz. These high beam quality, millisecond duration laser pulses are well suited to applications that require controlled heat deposition within small volumes of material, which because of the operating wavelength typically means in materials with some water content.

Work is in progress to increase the cw laser output power to several Watts by use of a longer traditional laser resonator instead of the microlaser chip. Meanwhile, work is also in progress to scale the pulse energy and peak power in the quasi-cw regime of operation by using higher peak power pump laser diodes and the current Er:YAG microlaser chip, with the goal of generating >5 mJ in 1 ms.

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