Multi-Watt Average Power Nanosecond Microchip Laser and Power Scalability Estimates

Oleg A. Konoplev[a], **Alexey A. Vasilyev**[a], **Antonios A. Seas**[b], **Anthony W. Yu**[b], **Steven X. Li**[b], **George B. Shaw**[b], **Mark A. Stephen**[b], **Michael A. Krainak**[b]

[a]*Sigma Space Corporation, 4400 Lottsford Vista Road, Lanham, MD, 20706*

[b]*NASA Goddard Space Flight Center, Laser and Electro-Optics branch, MC 554, Greenbelt, MD 20771*

Email: oleg.a.konoplev@nasa.gov

Abstract: We demonstrated up to 2 W average power, CW-pumped, passively- Q-switched, 1.5 ns monolithic MCL with single-longitudinal mode-operation. We discuss laser design issues to bring the average power to 5-10W and beyond.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched; (010.3640) Lidar.

1. Introduction

High average power, ~10-20W, compact, efficient and reliable nanosecond sources, with repetition rate of 10KHz and good beam quality,M2~1-1.5, spectral width of ~10 pm or narrower are needed for space ranging applications [1]. Passively Q-switched microchip lasers (MCLs) are one of the best candidates for current and future space ranging applications. MCLs are compact, efficient, monolithic, cavity-alignment-free, short cavity, narrow frequency sources for generation of ns to ps pulses with multi- 100 uJ pulse energies multi-kW peak powers [2,3] MCLs are currently in maturation stage. Their scalability to MW peak power and multi-Watt average power have been experimentally demonstrated. A 1.7 MW-peak power was demonstrated in QCW operation from Nd:YAG/Cr4+:YAG microlaser. Up to 4 pulses separated by 100 us, with spatial beam quality of M2~1.2, 3mJ each, with pulse duration of 1.2 ns were generated at 10 Hz QCW regime [4]. With optimization in laser cavity design, average powers of 2.6-4.2W with pulse durations 16-48 ns were reached in CW pumping mode [5]. It is worth to note that pulse repetition rate can be stabilized with addition of pump modulation to a sub 1% r.m.s. jitter level[6]. In this report, we demonstrate a medium-power version of monolithic Nd:YAG/Cr4+:YAG MCL with pulse duration of 1.5 ns and average power up exceeding 2W with relatively good, Gaussian beam. We also discuss possibility of scaling the design to 10W of average power while maintaining good beam quality.

2. MCL description and experimental results

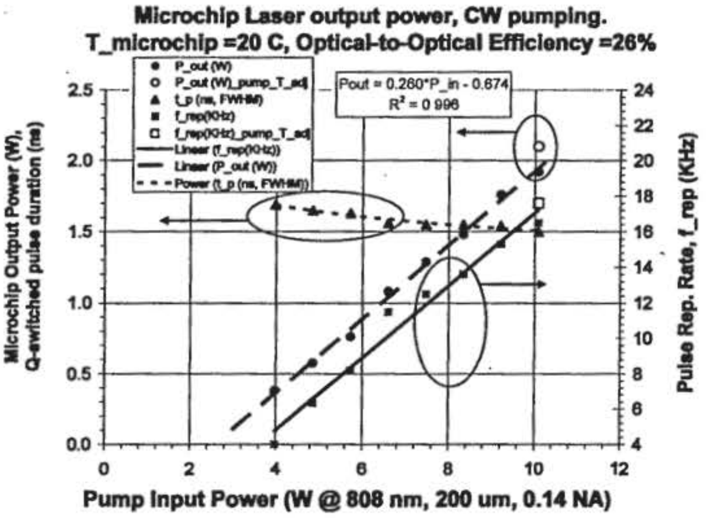

Figure 1. Output Power (W), pulse duration, FWHM (ns) and repetition rate (kHz) of monolithic, passively Q-switched MCL versus Pump Input Power (W) in CW pumping conditions. At 10W of pump power, the pump spectrum was adjusted by changing pump heatsink temperature by 1.5C. This is shown by open circle and open square datapoints for power and PRR. The spectrum of pump shifted by 0.5 nm and pump was coupled more efficiently. For all other datapoints pump was only varied in forward bias current.

A monolithic microchip slab with 2x2x16 mm3 dimensions was made by diffusion bonding technique, similar to the described in [2,3,7]. The slab consisted of two 2-mm undoped YAG outer sections and two 3mm and 4 mm 1.1wt% doped Nd:YAG inner sections. The 5 mm-long saturable absorber (SA) was sandwiched in the center of the cavity, between two doped sections in order to maximize the probability of single-longitudinal mode operation. This also offers us the possibility of end-pumping slab from both sides and ability to spread thermal load along cavity length. So far, we pumped the slab only from one side. All results reported in this work are from one-side pumping. The pump-side end-facet that contained undoped YAG section and followed by 3mm Nd-doped YAG section was HR1064/AR808 coated. Another facet was coated with reflectivity of 40% at 1064 nm. We placed the slab symmetrically in 14-mm-long copper heatsink similar to [2]. The pump was 808 nm fiber-coupled diode laser. The fiber had diameter 200 um and NA=0.14. We focused pump power to approximately the center of 3-mm doped section with 1:1 imaging optics.

The experimental results for average power, Q-switched pulse duration and pulse repetition rate at CW pumping conditions are shown in Figure 1. The temperature of the MCL heatsink was maintained at 20C±2C throughout all pump conditions. The 808 nm pump heatsink temperature was controlled with 0.25C accuracy. We observed 26% of optical-to-optical slope efficiency and overall optical-to-optical efficiency at or near 15% for 1W output power with about 2% jitter. Operating MCL at 30C reduced power for about 10-15% or less. As thermal resistance of junction-to-heatsink of the pump laser was finite, when pump power was increased from 4W to 10W, the pump output was slowly drifted off the optimal wavelength. We made one re-adjustment at the 10W pump level to maximize MCL average power and pulse repetition rate (PRR). Pump temperature adjustment by 1.5C improved MCL average output power from 1.9W to 2.1W, PRR increased from 16.5 kHz to 17.6 kHz. Pulse duration did not change. The pump-adjusted average power and PRR are shown with corresponding open circle and open square marks. The laser is capable of operating in CW mode up to 2.7W of average output power.

The spatial and temporal profiles of the MCL at 1.1W and at 2.1W are shown on Figure 2.

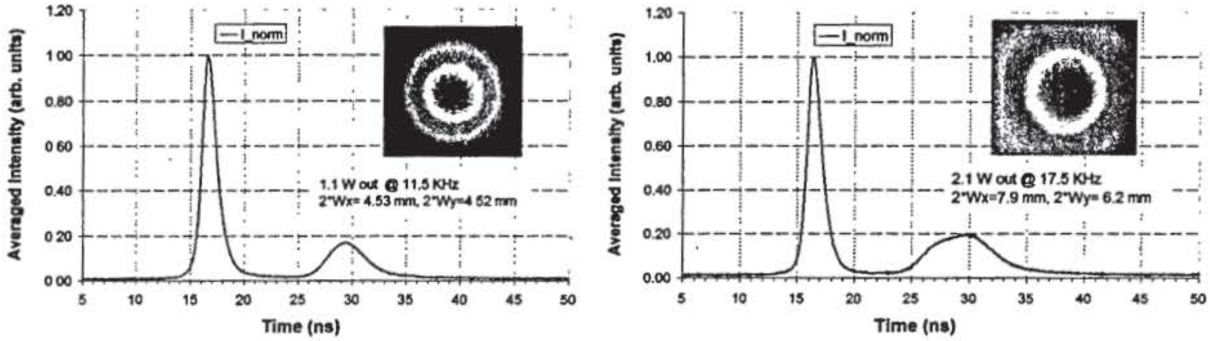

Figure 2. Spatial and temporal profile of the beam out of MCL. Temporal profile was recorded with 12 GHz bandwidth system and represent an average of about 20 measurements. We have not observed any beating within the main pulse. Spatial (far-field) profile was recorded at 47 cm from the output facet of MCL. The temporal profile was recorded by detecting diffused (i.e. spatially integrated) reflection of the beam.

We observed substantial afterpulse at the distance ~ 13-14 ns after the main pulse similar to the described in [7]. The afterpulse is believed due to the excitation of a higher transverse mode in the resonator cavity [7]. It is considered objectionable feature for LIDAR applications. It can be minimized or removed completely by careful pump-to-MCL mode matching [7]. It also can be further reduced through amplification of the MCL pulse in the gain-saturated amplifier and/or through nonlinear frequency conversion. Although overall conversion efficiency slope did not change when we ramp pump power to 10W, the main pulse energy grew much slower, from 65 uJ to 69.5 uJ when average output power increased from 0.58W @ 6.35kHz to 1.1W @ 11.5 KHz. When output power increased from 1.1W to 2.1W, the main pulse energy remained approximately constant (less than 1% increase observed) at 70 uJ/pulse level, while afterpulse contribution to total energy increased from 27% to 40%. We also observed shortening of main pulse length from 1.65 ns to 1.5ns and increase in far field divergence similar to [2,3]. At 1.1W spatial quality of the beam, M2 estimated to be near ~1.1-1.3. Due to the observed temporal profile it is believed that radiation out of this MCL (main pulse) is single-longitudinal mode. Relevant tests are underway. More details about this MCL behavior will be published elsewhere.

3. Scaling monolithic MCL to higher average and peak powers

We limit our discussion to Nd;Cr4+;YAG MCLs. Although Yb:YAG -based MCLs are scalable, especially in peak powers, but not so easily in average power, this is outside the scope of this short presentation. The design of the considered MCLs can be further optimized. In current design we deposited about 75-85% of the pump energy within 3mm of the 16 mm cavity. The sizeable part of the residual energy was deposited in 5mm long SA section which was positioned in the middle of the cavity. It is estimated that optimization of the cavity design and better thermal management can ramp up peak and average power by at least factor of two to three in assumption of maintaining material quality and low absorption and scattering losses inside the cavity. We have been able to observe 10-20% pulse energy increase with pump waist increase from 200 to 250 um. The laser was operated up to 7 kHz in CW mode with approximately the same ~ 1W output power. When waist is increased, the threshold pump power is increased as well. As the result, MCL may start lasing at distorted conditions even near threshold. For any working MCL design there is a range of pumping conditions when lasing is stable and spatial and temporal quality of the pulse are not compromised. The design presented here is capable of dissipating about 5-6W of pump power without thermal and nonlinear distortions but is capable of producing CW train of the Q-switched pulses up to ~ 10-12W of CW pump power. 5-10W output power laser must manage ~ 50-100W of pump power. This is considered feasible for mulit- KHz, 1 ns operation. Corresponding QCW operation was already demonstrated

To be able to scale power of a MCL, the simple set of equations for pulse duration and energy of the pulse should be established. The ability to support CW pump operation should be verified through thermal modeling and thermal degradation measurement of MCL components.

The 1-dimensional model of MCL dynamics, including excited state absorption is well developed. [3,5]. Although not rigorous, the simplest scaling equation for MCL pulse duration that explicitly includes the most important cavity parameters and matches well with experimental data was noted in [2] and re-emphasized in [8],

$$t_{FWHM} \cong \frac{3.52T_{rt}}{\Delta T_{SA}} \tag{1}$$

where, T_{rt} is round-trip cavity time and ΔT_{SA} is the modulation depth of the SA or difference in single-pass transmission of the bleached state and closed state. The formula assumes that all non-SA intracavity losses are minimal. The Eq. (1) was extensively verified with semiconductor saturable absorbers [8]. We compared our design and 7 similar molonlithic Nd/Cr4+:YAG designs [2,3] and found 30% or better agreement with experimental data for all 0.5-2 ns cavities. Only for 0.3 ns HPMCL-4 laser Eq. (1) underestimated the pulse duration by 45%. For our cavity, the calculated value is about 1.45 ns. With practically feasible SA modulation depth, the cavity made with various YAG undoped or YAG-doped materials can be as long as 20-25 mm to maintain the pulse within ~ 1-1.5 ns pulse duration. The gain medium can be distributed along ~ 15-18 mm length. This is about 5x larger than pump absorption length reported in this work.

The second most important scaling parameter of the passively Q-switched MCLs is the energy of the pulse. The experimentally confirmed pulse energy matched well to [3]

$$E_p \approx \frac{F_{sat} A_{eff} * \ln(Go)}{0.623} \tag{2}$$

where F_{sat} is the linewidth reduction adjusted saturation fluence in standing-wave resonator, A_{eff} is the effective beam area and Go is the single-pass gain at the onset of Q-switching. With saturation fluence of Nd:YAG of ~0.29 J/cm2 and linewidth reduction factor of 0.41, we get Fsat ~ 0.35 J/cm2. With $1/e^2$ waist of the MCL of 70 um [M2= 1.14] and ln(Go) ~1.2, we get estimated 70 uJ/pulse, which is in excellent agreement with experimentally observed values. The 2-3x larger pump waist and MCL waist are probably feasible in QCW regime as lasing threshold scales with square of the pump waist. Spreading pump power deposition over 10-15 mm distance and using 400-500 um pumping we expect to bring single pulse power to 0.4-0.5 mJ and average power to 3-5W while maintaining pulse duration and beam quality. Further optimization of the cavity and thermal design improvements may create another 3dB boost in average power scaling.

In conclusion we demonstrated 1.5 ns monolithic MCL capable of emitting powers in excess of 2W in CW pumping conditions at PRR ~10-15 kHz. We matched our theoretical predictions with experimental data and discussed possibility of increasing average pump power to 5-10W level from a single monolithic MCL chip.

4. Acknowledgement

This work was supported under NASA contract NNG09CP09C for ICESat-II ATLAS instrument.

5. References

[1] Anthony W. Yu; Mark A. Stephen; Steven X. Li; George B. Shaw; Antonios Seas; Edward Dowdye; Elisavet Troupaki; Peter Liiva; Demetrios Poulios; Kathy Mascetti, "Space laser transmitter development for ICESat-2.mission," in Solid State Lasers XIX: Technology and Devices, W. Andrew Clarkson; Norman Hodgson; Ramesh K. Shori, Editors,., Vol. 7578 of of Proc. of SPIE, Bellingham, WA, 2010

[2] J.J. Zayhowski, C. Dill III, C. Cook and J.L. Daneu, Mid- and high-power passively *Q*-switched MCLs. In: M.M. Fejer, H. Injeyan and U. Keller, Editors, *OSA TOPS Vol. 26 Advanced Solid State Lasers*, Optical Society of America, Washington, DC (1999), pp. 178-186.

[3] J.J. Degnan, J.J. Zayhowski, SLR2000 microlaser performance: theory vs. experiment, in: W. Schlüter, U. Schreiber, R. Dassing (Eds.), Proceedings of the 11th International Workshop on Laser Ranging, Vol. 2, Frankfurt am Main, 1999, p. 453-468

[4] M. Tsunekane, T. Inohara, A. Ando, K. Kanehara, and T. Taira, "High Peak Power, Passively Q-switched Cr:YAG/Nd:YAG Micro-Laser for Ignition of Engines," in *Advanced Solid-State Photonics*, OSA Technical Digest Series (CD) (Optical Society of America, 2008), paper MB4.

[5] N. Pavel, J. Saikawa, S. Kurimura, and T. Taira, "High Average Power Diode End-Pumped Composite Nd:YAG Laser Passively Q-switched by Gr4+:YAG Saturable Absorber," Jpn. J. Appl. Phys. 40, 1253-1259 (2001).

[6] Jianwu Ding, Allen R. Geiger, "Repetition-Rate-Stabilized High Power Passively Q-Switched Nd:YAG MCL," in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper CFA7.

[7] Randal L. Schmitt, "Monolithic passively Q-switched Cr:Nd:GSGG microlaser," in Optical Technologies for Arming, Safing, Fuzing, and Firing, William J. Thomes, Jr., Fred M. Dickey, Eds., Vol. 5871 of OSA Proceedings of SPIE, Bellingham, WA, 2005

[8] G. Spuhler, R. Paschotta, R. Fluck, B. Braun, M. Moser, G. Zhang, E. Gini and U. Keller, "Experimentally confirmed design guidelines for passively Q-switched MCLs using semiconductor saturable absorbers", J. Opt. Soc. Am. B 16 (3), 376 (1999)