A compact single-longitudinal mode microchip laser operating at 532 nm

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Abstract—In this paper we present a compact, single-longitudinally mode diode pumped microchip laser operating at 532 nm. The laser is based on a monolithic Nd:YVO_4/YVO_4/KTP laser resonator. It is fully integrated with specially designed driving electronics, power supply unit mechanical assembly, pumping unit, beam expander and can work as an independent device. Thanks to the monolithic resonator design and low noise driving electronics the laser is highly resistant to environmental hazards. The output power, passive frequency stability and linewidth were at the level of 55mW, $3\cdot10^{-9}$ @ 1s mean time and 25kHz, respectively.

The development of single frequency, stable, narrow linewidth laser sources operating mainly in the visible wavelength range determines rapid progress in many applications such as holography, precise interferometry, spectroscopy, vibrometry and flow cytometry [1-3]. Because of their excellent beam quality, very good spectral properties, quite compact design and cost-effective construction, He-Ne lasers are widely used in those applications. However, low output power at the level of few hundreds microwatts in a single frequency regime limits the usage of these lasers. The requirements are also well fulfilled by solid state lasers which offer much more power.

In contrast to the He-Ne lasers, the gain media used in solid state lasers are characterized by a homogenously broadened gain curve. The single mode operation of such lasers is limited by a spatial hole burning (SHB) effect [4-5]. In order to eliminate such an undesired effect and obtain stable single frequency operation, several methods have been developed. A short laser cavity with mode spacing comparable to the gain width can be used [6-8], but effective internal second harmonic generation is difficult with limited output power. A twisted mode technique allows to eliminate the standing-wave pattern and uniformly saturate the gain [9-11]. However, this technique cannot be used with birefringent gain media such as Nd:YVO_4. The SHB effect can also be eliminated in an unidirectional ring resonator [12] and in monolithic nonplanar ring oscillator setups [13-14]. Nevertheless, ring resonators require extra internal elements or special, complex gain crystal cutting. Using an external etalon [15] and a birefringent filter inside the laser cavity [16-18] can limit the SHB effect. The application of a double cavity [19] and volume Bragg grating [20] can also effectively force single mode operation.

In order to fulfill the criteria of high resistance to environmental hazards and compactness, the monolithic laser resonator with mirrors directly deposited onto crystal surfaces is preferred. Such resonators are adjustment free, relatively cost-effective and offer very good frequency and power stability. Watanabe *et al.* [21] presented a single frequency monolithic Nd:YVO_4/KTP laser operating at 532nm with an output power of 105mW. However, single mode operation was obtained only for well-defined pumping powers and resonator temperatures. Those limitations can be eliminated by using a laser resonator with bidirectional traveling-waves [22]. Single frequency operation in a relatively broadband wavelength range from 1064nm to 1064.3nm with output powers up to 700mW@1064nm and 80mW@532nm using Nd:YVO_4 gain crystal were obtained.

The monolithic laser resonator supporting single frequency operation at 532nm [23-25] and at 1064nm [26] was also reported by the authors of this paper. The single mode operation is obtained using a birefringent filter formed by an undoped YVO_4 (polarization sensitive beam displacer) and nonlinear crystal acting as a waveplate (KTP@532nm, YVO_4@1064nm). The principles and theoretical background of single mode operation in such resonators were reported previously [23-26].

In this paper we present a compact, autonomous single-longitudinally mode diode pumped microchip laser operating at 532nm with an output power of 55mW and a very good passive frequency stability of $3\cdot10^{-9}$@ 1s.

The laser is based on an optimized monolithic Nd:YVO_4/YVO_4/KTP laser resonator with total dimensions of $1\times1\times11$ mm^3 depicted in Fig. 1 [25]. The laser resonator consists of: 1mm long, 1% Nd-doped YVO_4 gain crystal, 5mm long, undoped YVO_4 beam displacer and a 5mm long, II-type phase matched KTP crystal. The laser mirrors were directly deposited onto the outer side of Nd:YVO_4 crystal (AR@808nm and

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HR@1064nm) and the outer surface of the KTP crystal (HR@1064nm and AR@532nm). The crystals were bonded together using UV curable, high refractive index adhesive (NTT).

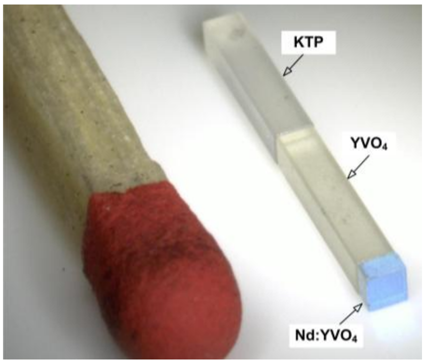


Fig. 1. Photography of monolithic $Nd:YVO_4/YVO_4/KTP$ resonator.

The laser resonator was mounted in a cooper block. The pumping beam focused on the gain crystal by GRIN lens was generated by a 1W semiconductor laser operating at 808nm (QA-808-1000-030, Axcel Photonics). The generated single frequency output beam was output coupled by a beam expander with a magnification of ×10. Both the pumping module and laser resonator temperatures were precisely controlled (accuracy: ±0.003^{o}C) by Peltier elements equipped with dedicated and miniaturized driving electronics. The pumping diode current was also controlled with accuracy of 30μA@600mA by a miniaturized current source. All the designed subsystems were integrated on an air cooled aluminum heat sink. The fully equipped, autonomous laser system with dimensions of 40×120×55mm^3 is presented in Fig. 2.

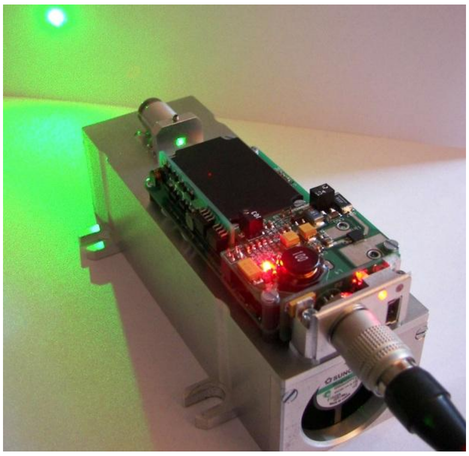


Fig. 2. Photography of compact single frequency laser operating at 532nm.

The laser performance was measured using an optical spectrum analyzer (OSA, Yokogawa AQ6370B), RF spectrum analyzer (Agilent EXA N9010A), power meter (Coherent, LabMax II) and frequency counter (Lasertex, OC-1100).

The optical spectrum of the developed laser was measured at the fundamental wavelength with a 0.02nm resolution by OSA and is presented in Fig. 3. The single mode operation was observed in a temperature range from 20^{o}C to 29^{o}C.

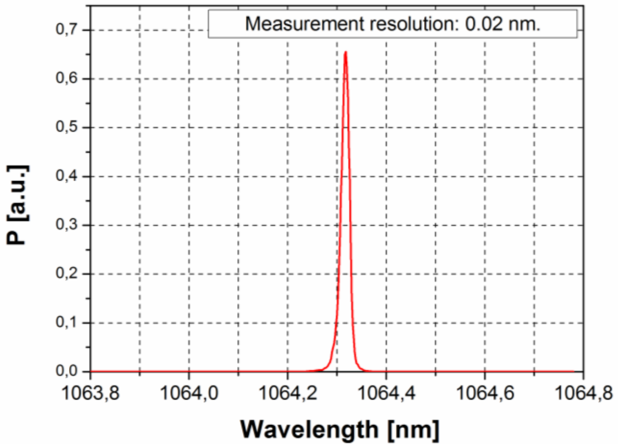


Fig. 3. Optical spectrum of single mode laser.

The heterodyne setup of two lasers was assembled in order to confirm single frequency operation with high resolution. The beating signal was analyzed at 532nm. The RF spectrum (Fig. 4) clearly confirms single frequency operation – only one heterodyne signal at 320MHz is observed. There is no sign of parasitic beating signals resulting from higher order modes in the output beam. The linewidth of the laser was measured and was at a level of 28kHz (inset graph in Fig. 4). The signal to noise ratio (SNR) of 45dB is limited by intensity noise at 1.2MHz. It can be further improved by an additional feedback loop. The frequency temperature tuning coefficient of 660MHz/0.1^{o}C was measured.

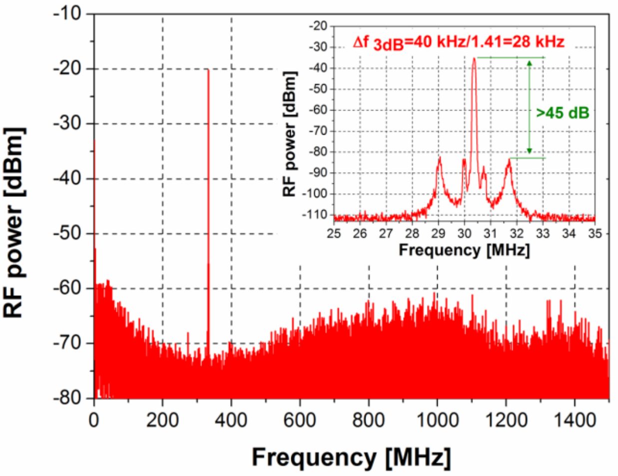
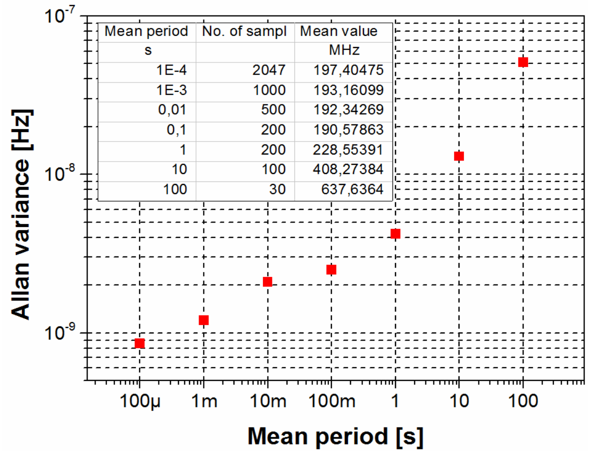


Fig. 4. Heterodyne signal of two designed lasers. Inset graph represents the measured linewidth of 28kHz.

The combination of a monolithic, adjustment free laser resonator with a miniaturized and accurate driving electronics results in very good passive frequency stability at a level of $3{\cdot}10^{-9}$@ 1s mean time, confirmed by measured Allan variance (Fig. 5). Obtained results are characterized by a frequency drift which is typical of passive frequency stabilization.



Mean period s	No. of sampl	Mean value MHz
1E-4	2047	197,40475
1E-3	1000	193,16099
0,01	500	192,34269
0,1	200	190,57863
1	200	228,55391
10	100	408,27384
100	30	637,6364

Fig. 5. Passive frequency stability of the laser.

The maximum power was generated at a laser resonator temperature of 27.7°C. In such conditions the laser pumped with 450mW@808nm generated 55mW@532nm (optical to optical efficiency of 12.2%). Thanks to the miniature and monolithic design the output power stability was at the level of ±0.4% (Fig. 6).

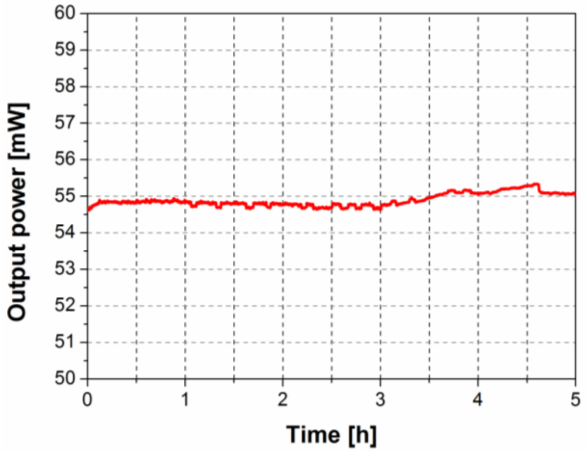


Fig. 6. Output power stability.

In conclusion, we have presented a compact, fully autonomous, single frequency laser based on a monolithic Nd:YVO_4/YVO_4/KTP laser resonator. The laser operates with an output power of 55mW. The miniature design results in a very good frequency and power stability of $3{\cdot}10^{-9}$@ 1s mean time and ±0.4%, respectively. The laser parameters are comparable to those offered by commercially available laser systems.

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