1 W of stable single-frequency output at 1.03 µm from a novel, monolithic, non-planar Yb:YAG ring laser operating at room temperature

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Abstract: We demonstrate, for the first time to our knowledge, a longitudinally diode-pumped, monolithic ytterbium ion-doped YAG non-planar ring laser (NPRO). We achieved a continuous-wave (cw) single-frequency output power of 1 W with 45.0 % slope efficiency and a beam quality factor of M^2<1.1. In view of iodine frequency stabilization we have characterized the frequency tuning properties and have measured the relative intensity noise. Additionally, 6.1 mW second harmonic power at 515 nm was achieved using a periodically poled KTP crystal in a single-pass setup.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state; (140.3570) Lasers, single-mode; (140.3560) Lasers, ring; (140.5680) Rare earth and transition metal solid-state lasers

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1. Introduction

For many years, diode-pumped continuous-wave (cw) monolithic non-planar ring oscillators (NPROs) [1,2] are well-known as intensity and frequency stable single-frequency laser sources with several advantages as compactness, reliability, frequency tunability, output powers up to a few watts and excellent beam quality compared to other single-frequency lasers such as micro-chip lasers [3] and monolithic twisted-mode lasers [4], respectively. As a common application, frequency-doubled Neodymium ion-doped YAG (Nd:YAG) NPROs (fundamental wave at 1064 nm, second harmonic wave at 532 nm) are widely used for high-precision optical frequency standards based on laser frequency stabilization to hyperfine transitions of molecular iodine [5,6]. The compact and efficient NPRO design enabled the possibility to develop transportable iodine-based frequency standards for international comparisons. In the last twenty years, the frequency stability was significantly increased using sophisticated stabilization techniques and setups to reduce residual noise on the stabilization signal and the linewidth of the iodine transition, respectively. The use of iodine transitions at wavelengths below 532 nm could increase the frequency stability as the natural linewidth decreases towards the dissociation limit. Especially, the wavelength region of 523-498 nm yields a number of highly promising candidates for future optical frequency standards [7], but is not accessible with frequency-doubled Nd:YAG NPROs emitting at 1064 nm fundamental wave. Wavelengths below 532 nm can be easily accessed by frequency-doubled Titan-Sapphire lasers and by argon-ion lasers at 515 nm, but these laser systems do not offer the advantages of NPRO lasers such as compactness, reliability, efficiency and stability. On the other hand, single-frequency Ytterbium YAG (Yb:YAG) lasers at a wavelength 1.03 µm, second harmonic wave at 515 nm, could provide the appropriate wavelength to use transitions near the dissociation limit of iodine. However, published Yb:YAG laser systems are based on discrete element resonators with at least one additional intra-cavity optical element (e.g. etalon) to enforce single-frequency operation [8,9]. Compared to the NPRO design these lasers are not well suited for precise frequency stabilisation due to the fact that they are highly susceptible to acoustics, vibrations and air turbulences.

The direct and obvious solution would be a frequency-doubled Yb:YAG NPRO but this could not be realized so far because of several problems accompanying the use of Ytterbium as gain media. In contrast to Nd:YAG at the emission wavelength of 1064 nm, the lower laser level of the $^2F_{5/2}$ to $^2F_{7/2}$ transition in Yb:YAG is thermally populated at room temperature. Thus, the Yb laser is a quasi-three level system and at least 5.5% of all Yb ions must be pumped into the upper laser level to achieve gain material transparency while the minimum transparency pump intensity is essentially zero for Nd:YAG [10]. Consequently, high pump power densities are required for Yb oscillators to overcome optical losses and reach the laser threshold. Furthermore, in the classical NPRO design strong re-absorption losses occur in unpumped regions as the pump light is only absorbed in the first few millimeters of the crystal. To realize a monolithic Yb single-frequency laser, another handicap is the ten times broader laser transition linewidth. Hence, without any additional intra-cavity elements like etalons, single frequency operation could not be achieved so far.

In the present paper, we report, for the first time to our knowledge, on a novel, continuous-wave single-frequency Yb:YAG NPRO overcoming the previously described issues. By using a special laser crystal design, we achieved efficient laser operation at room temperature with

1W output power at 1.03 µm enabling sufficient second harmonic generation for laser frequency stabilization to molecular iodine. We report on the measured laser parameters such as power, laser threshold, slope efficiency and beam quality. With regard to the application of laser frequency stabilization, we also characterized the fast and slow frequency tuning properties of the device. Moreover, the relative intensity noise for a free-running and for an actively noise-reduced laser has been measured. Finally, we have realized second harmonic generation using a simple, single-pass set-up with a periodically poled KTP (PPKTP) crystal as required for iodine frequency stabilization.

2. Laser crystal design

The laser design is based on a double diffusion-bonded monolithic crystal [11] with dimensions 7 mm (length) x 4 mm (width) x 2 mm (height) as shown in Fig. 1. The first crystal segment is made of undoped YAG to avoid spatial hole burning effects which prevents laser operation in a stable fundamental mode at high pump power levels (2-3W). The front surface is dielectrically coated for high transmission at the pump wavelength of 940 nm and a few percent output coupling at the laser wavelength. The second crystal segment is the active Yb:YAG gain media for the laser process with 5.0 at% doping concentration. The third crystal part is again undoped YAG and is used as total internal reflector to realize the non-planar beam path similar to original NPROs. We have chosen undoped YAG to significantly reduce re-absorption losses. Stable single-frequency operation is accomplished by enforcement of unidirectional operation owing to an intrinsic optical diode [1]. To achieve the optical diode we applied a permanent magnetic field of ~0.3 T along the crystal. Because of the 45° out-of-plane angle of the beam inside the composite crystal, the ring laser is tolerant to small geometry variations caused by the manufacturing process. Additionally, the strength of the optical diode is increased by a factor of approximately 4 compared to a 90° out-of-plane angle. The calculations for optimising the NPRO geometry were done using the theory from Nilsson et. al. [12].

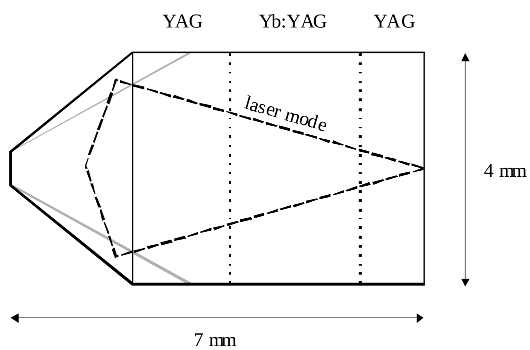

Fig. 1. Schematic draw of the double-diffusion bonded Ytterbium NPRO crystal.

3. Experiments

As a pump source, we use two temperature stabilized nLight laser diodes including fast axis collimation delivering a combined output power of up to ~4.6 W. The laser diode temperatures are tuned to the absorption maximum of Yb:YAG at 940.5 nm to provide efficient absorption. The pump light is collimated and focussed into the composite crystal. The pump focus has approximately the same size as the expected fundamental mode size inside the laser cavity. The laser emission occurs at the $^2F_{5/2}$ to $^2F_{7/2}$ transition with laser wavelength of 1031.0 ± 0.05 nm measured with an optical spectrum analyzer (ANDO AQ-6315A). A dielectrically coated mirror with high transmission at the pump wavelength and high reflectivity at the laser wavelength was used to separate the laser and pump light.

The crystal was clamped on a gold plated heat sink and precisely stabilized in temperature with a TEC. Operating the Yb laser at 20°C, we measured a laser threshold of 1.63 W and a

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maximum single-frequency TEM_{00} power of 1002 mW with 4.59 W pump power in front of the laser crystal. The measured laser power versus pump power is illustrated in Fig. 2 with the diode temperature held at constant temperature and optimized at maximum laser power. From these numbers a slope efficiency of 45.0 % (power level > 500 mW) and a maximum optical to optical efficiency of 21.8 % was calculated. We measured the single-longitudinal-mode spectrum using a scanning, confocal Fabry-Perot Interferometer (FPI, Finesse of ~100) at the maximum laser output power as illustrated in Fig. 2. The free spectral range of the FPI was approximately 2 GHz as indicated in the figure. The absence of any peaks between the main resonances of the interferometer clearly indicates the operation on one single longitudinal and transverse frequency.

In view of efficient frequency doubling or for fiber coupling applications, we characterized the beam profile and beam quality at maximum output power. With a CCD camera we measured an overlap with a Gaussian fit of 99.5 %; beam quality was measured using the knife-edge method. For that purpose, we created a focus and measured the beam diameter at different positions. From this caustic we obtained an M^2 value of 1.00 and 1.05 (±0.05), for x and y axis respectively. Using a 20 mm long PPKTP crystal in a simple single-pass setup, we generated 6.1 mW second harmonic radiation at 515 nm with 777 mW infrared power in front of the crystal. This power level is sufficient for iodine frequency stabilization [5, 6].

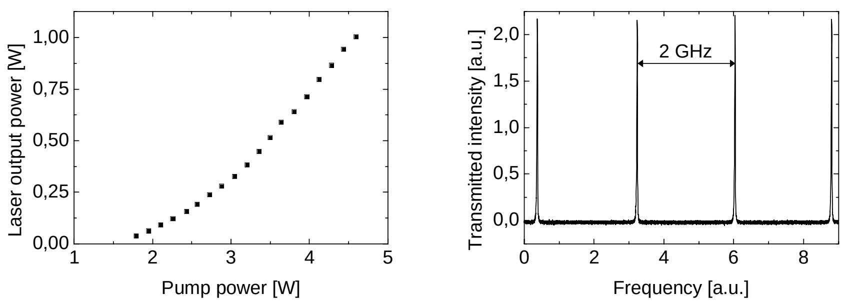

Fig. 2. Single frequency output power (left) and corresponding longitudinal-mode spectrum observed with a scanning Fabry-Perot interferometer with 2 GHz free spectral range (right).

For iodine frequency stabilization an actuator is required to influence the laser frequency. In general, three different techniques can be used for simple and efficient frequency tuning of NPROs namely by changing the laser crystal temperature [13], by using a piezo-electric transducer (PZT) glued on the laser crystal [14] and by changing the pump diode current [15]. By changing the laser crystal temperature we measured at power levels >500 mW a minimum mode-hop free tuning range of 9 GHz and a total frequency tuning of >32 GHz using a wavemeter (Toptica WS-6) with an absolute accuracy of ±600 MHz. Simultaneously, we verified single-frequency operation of the NPRO laser with the FPI. From the data we calculated a temperature tuning coefficient of -3.2 GHz/K which is similar to that of Nd:YAG NPROs. Varying the laser output power from 1 W to 0.5 W by changing the laser diode current, we observed a frequency tuning from 290.7809 THz to 290.8877 THz corresponding to a frequency shift of ~100 GHz. This wide tuning range is advantageous for iodine stabilization as many different transitions can be accessed. To lock a laser to a molecular transition, a fast frequency actuator is required. Therefore, we tested the capability of frequency tuning using a PZT as actuator glued on top of the laser crystal. Applying 100 V (DC), we measured a tuning coefficient of 1.5 MHz/V which is comparable to Nd:YAG NPROs. The first resonance of the PZT is above 100 kHz which is sufficiently high for frequency stabilization loops.

4. Laser intensity noise

Laser noise properties strongly influence the frequency stabilization accuracy to molecular iodine. Therefore, the intensity noise was characterized and is described below. To reduce the intensity noise we used a feedback control loop (noise eater, NE) acting on the laser diode current [16]. The laser was running at maximum output power. With an out-of-loop photo detector, we detected a few ten mW and measured the intensity noise using an electrical spectrum analyser (Hewlett Packard L1500A, 9 kHz-1.5 GHz). Together with the DC voltage of the photodiode, we calculated the relative intensity noise (RIN) which is illustrated in Fig. 3 for active and inactive NE operation.

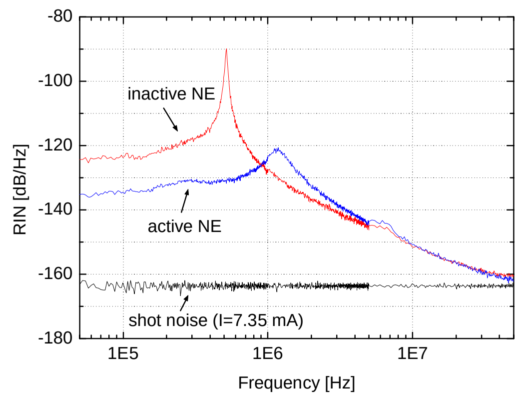

Fig. 3. Relative intensity noise (RIN) of the Ytterbium NPRO with and without active noise reduction using a noise eater (NE).

The intensity noise is dominated by the peak of the laser relaxation oscillation at 516 kHz. Above the relaxation oscillation a ~1/f decrease can be observed. However, a decrease of ~$1/f^2$ is usually observed for Nd:YAG NPROs. Thus, we verified the influence of the pump source on the laser intensity noise by measuring the corresponding transfer function. Modulating the laser diode current, we measured the expected ~$1/f^2$ decrease above 1 MHz. Hence, at high frequencies the laser intensity noise is not dominated by the pump power fluctuations but by internal noise processes [17]. Further theoretical and experimental effort is necessary to describe in detail the noise processes of quasi-three level Yb:YAG NPROs.

5. Conclusion

In conclusion, we have demonstrated for the first time to our knowledge, a monolithic Yb:YAG NPRO with a diffraction limited, single-frequency output power of >1W at 1.03 µm. Further, we characterized the frequency tuning properties of the laser and measured the relative intensity noise. These measurements show that the Yb:YAG NPRO is a very interesting candidate for frequency stabilization and fiber amplification experiments.