Passively Mode-Locked 1.3-μm Multi-GHz Nd : YVO$_4$ Lasers With Low Timing Jitter

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***Abstract*—We demonstrate diode-pumped passively mode-locked 1.34-μm Nd : YVO$_4$ lasers with repetition rates of 5 and 10 GHz. Passive mode locking is achieved by using a novel GaInNAs-based saturable absorber mirror. Phase noise measurements prove the low timing jitter that can be obtained with this kind of lasers.**

***Index Terms*—Laser absorbers, laser noise, mode-locked lasers, neodymium, solid lasers.**

I. INTRODUCTION

DIODE-PUMPED passively fundamental-mode-locked solid-state lasers with very high pulse repetition rates [1] have won wide recognition as low noise pulse generating lasers (PGLs) for telecom applications [2]–[4]. Fundamental passive mode-locking generates a stable picosecond pulse train with high pulse quality without the need for any radio frequency drive electronics. The pulse train is characterized by a high contrast ratio, very low intensity and timing noise, relatively high average power, and excellent optical signal-to-noise ratio [4], [5]. The simplicity of the approach leads to reduced power consumption and cost of the system, while the ease of use is greatly enhanced compared to alternative approaches using harmonically mode-locked fiber ring lasers [6] or hybrid mode-locked semiconductor lasers [7]. When needed, the timing of the pulse train of the laser can be locked to an external clock signal, reducing the jitter even significantly below the quantum limit for a free-running passively mode-locked laser [8].

So far, we have presented this approach in the third telecom window using Er : Yb : glass as gain element around 1550 nm [5]. Here, we demonstrate the progression of this approach into the second telecom window, describing passively fundamental mode-locked Nd : YVO$_4$ lasers operating at 1342 nm with pulse repetition rates of 5 and 10 GHz. So far, the repetition rate of passively mode-locked solid-state lasers operating at 1.3 μm has been limited to $\approx$100 MHz [9].

II. Nd : YVO$_4$ LASER SETUP

Nd : YVO$_4$ is a well-known gain medium for solid-state laser technology. It can be pumped at 808 or 879 nm and shows gain at 914, 1064, and 1342 nm. It typically shows high power efficiency and can be produced in large quantities at very low cost. The emission cross section of Nd : YVO$_4$ at 1342 nm is $\approx 28 \cdot 10^{-20}\text{cm}^2$ [10], which is about four times less than at 1064 nm but relatively high compared to other solid-state gain media in this wavelength regime. This relatively high emission cross section helps to suppress Q-switched mode-locking instabilities [11], [12], which represents one of the main challenges for passively mode-locked solid-state lasers at these pulse repetition rates. It also explains why Nd : YVO$_4$ is a good choice for the gain material, although the emission wavelength is rather long for this telecom window (compared to other neodymium-doped crystals, e.g., Nd : YLF).

For passive mode-locking, we use a semiconductor saturable absorber mirror (SESAM) [13], [14]. In the multigigahertz (multi-GHz) regime, typical intracavity pulse energies are around or even below a nanojoule. In order to still sufficiently saturate the absorber, it needs to exhibit a very low saturation fluence, and the mode size on the SESAM needs to be very small (on the order of a few micrometers). This implies stringent requirements on the saturable absorber itself and on the cavity design.

The reason for the relatively low saturation fluence of $\approx$19 μJ/cm^2 of the novel SESAM used in this laser is two-fold. First of all, it makes use of a recently introduced GaInNAs absorber material [15] with high absorption cross sections and, thus, low saturation fluence. Additionally, we embedded the absorber material in an SESAM structure with enhanced optical field intensities in the absorber section and, thus, further reduce the saturation fluence of the device [16]. The antiresonant SESAM consists of a quarter wave SiN$_x$ cap layer, a 10-nm GaAs cap layer, a 10-nm GaInNAs absorber with a 79-nm GaAs spacer layer, grown by molecular beam epitaxy on top of a GaAs–AlAs Bragg mirror. It serves as an excellent device for mode-locked solid-state lasers with high repetition rates, as it provides low nonsaturable loss, low saturation fluence, adequate modulation depth, while the operation wavelength can be set by composition and postgrowth rapid thermal annealing [15].

Fig. 1 shows the laser setup, which is similar to the Er : Yb : glass cavity, described in [5]. It allows us to use relatively small laser mode sizes in the gain element and on the SESAM, which is, as mentioned, important at these repetition rates in order to fully saturate the SESAM and to suppress

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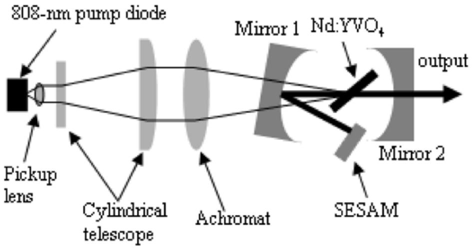

Fig. 1. Laser setup of the 5- and 10-GHz Nd : YVO$_4$ laser. Cavity lengths 30 and 15 mm, respectively.

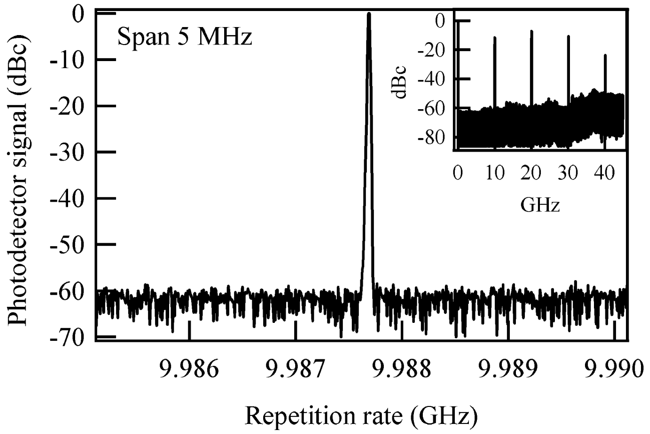

Fig. 2. Microwave spectrum of the 10-GHz continuous-wave mode-locked Nd : YVO$_4$ laser taken with a resolution bandwidth of 10 kHz. Inset: Microwave spectrum with 46-GHz span.

Q-switched mode-locking [11], [12]. We present two lasers with different pulse repetition rates. At 10 GHz, we want to exploit the limits of this approach in terms of pulse repetition rate. Additionally, we developed a similar 5-GHz version of the laser, in which we invested more mechanical engineering in order to obtain a ruggedized cavity setup to prove the low jitter levels that can be achieved with these kinds of lasers.

The over-all cavity lengths are 15 and 30 mm, respectively, for the fundamentally mode-locked 10- and 5-GHz lasers. We use an 808-nm pump laser diode from Bookham Technologies with 400-mW output power in a single transversal mode. The diffraction-limited pump beam allows us to achieve a small pump spot in the thin Nd : YVO$_4$ crystal, while maintaining a compact pump setup. Additionally, it excludes competition noise of transverse mode (existing in multimode lasers) on the pump signal which can be passed on to the laser output and degrade it. The diode is temperature controlled and the diode mount is air-cooled.

III. LASER PERFORMANCE

The average output power of the 10-GHz laser is 40 mW for a pump power of 400 mW. The free-space output of the laser is linearly polarized and diffraction limited. The microwave spectrum of the continuous-wave mode-locked Nd : YVO$_4$ laser at full pump power shows that Q-switching instabilities expected to be offset by ≈700 kHz from the main peak [17] are firmly suppressed (Fig. 2). The pulse duration is 7.3 ps, assuming a sech^2 pulse shape (Fig. 3). The measured output pulse energy is 4 pJ, resulting in a pulse peak power of 0.5 W. The center wavelength is at 1341.7 nm with a 3-dB bandwidth of 0.36 nm (Fig. 3).

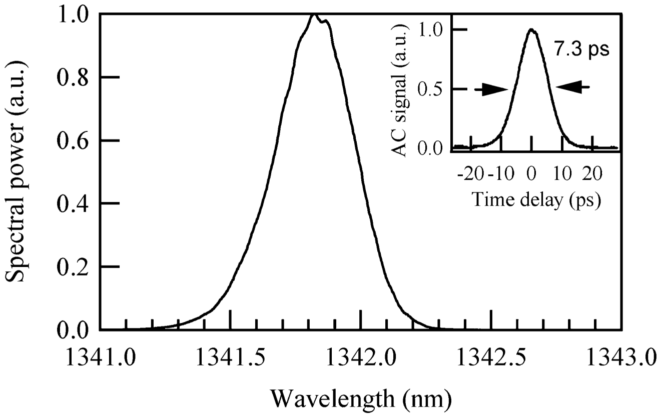

Fig. 3. Optical spectrum and autocorrelation (inset) of 10-GHz Nd : YVO$_4$.

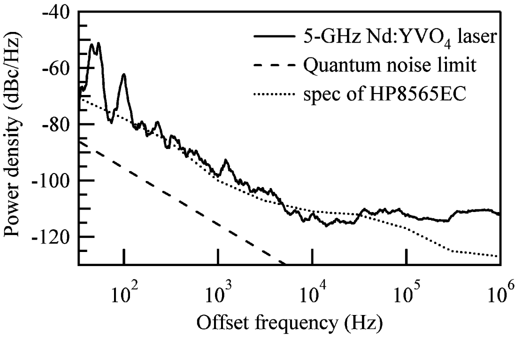

Fig. 4. Phase noise power spectral density for free running 5-GHz Nd : YVO$_4$ laser measured with von-der-Linde method together with calculated quantum limit and noise specifications for the microwave spectrum analyzer.

For optical clocking applications, we further developed a particularly compact and stable package of a 5-GHz version of this laser. It avoids the use of any translation stages. The different cavity elements are mounted directly on a single monolithic cavity frame. This leads to significantly reduced mirror vibrations and air currents in the pump and laser path. Additionally, the output is efficiently coupled into a polarization-maintaining fiber. The whole assembly is enclosed in a very compact package of only 41 × 33 × 175 mm^3. The performance of this laser is similar to the 10-GHz version (350-mW pump power, 45-mW output power in free space, 7-ps pulses, 0.47-nm optical bandwidth). Fig. 4 shows the timing phase noise power spectral density for the free-running output of this laser, measured with the von-der-Linde method [18]. Also shown is the specified noise of the reference oscillator of the microwave spectrum analyzer (Agilent 8565EC) used for this measurement and the calculated quantum limit according to an analytical model [19]. The model assumes influences of noise from spontaneous emission and cavity losses only, while ignoring possible cavity length fluctuations and assuming zero intracavity dispersion. One can see that the measurement is nearly completely limited by the noise of the microwave spectrum analyzer, apart from some ripples at 50 and 100 Hz that are caused by the power supply, and some increased high-frequency noise from the photodiode. Integration of the measurement system limited phase noise power spectral density from 33 Hz to 1 MHz yields a root mean square (rms) timing jitter of only 440 fs. This represents an upper limit for the rms timing jitter of the laser. Therefore, the free-running timing jitter of this laser is at most at the level of a 10-GHz Er : Yb : glass laser [8], possibly even well below it, and certainly low enough for clocking applications.

Furthermore, synchronizing the laser to an external clock signal with a phase-locked loop, should even flatten the phase noise curve for frequencies below the loop bandwidth of a few kilohertz. We expect jitter values similar to the stabilized Er : Yb : glass results (≈26-fs rms relative jitter between two 10-GHz Er : Yb : glass lasers, integrated from 6 Hz to 1 MHz [8]), as we are using the same type of elements: solid-state gain material, low-loss SESAM, single-mode diode pump laser, together with comparable intracavity powers, cavity losses, and pulse durations. With a recently introduced measurement method [8], the real jitter of this low noise source could be revealed. However, for this measurement, we will need two identical lasers or an electronic reference oscillator with significantly better timing phase noise

IV. CONCLUSION

We have demonstrated a passively mode-locked 10-GHz Nd : YVO$_4$ PGL operating at 1342 nm with 40-mW average output power and 7.3-ps sech^2 pulse duration. Key enablers are a newly developed SESAM with relatively low saturation fluence, based on a GaInNAs absorber and a novel device structure, the use of a single-mode pump laser, and an optimized cavity design. A mechanically ruggedized 5-GHz version of the laser has been developed, yielding very low free-running rms timing jitter with an upper limit of 440 fs (33 Hz to 1 MHz, instrument-limited). Pulse trains with considerably higher repetition rate, ultralow jitter, high contrast ratio, and shorter pulses can be expected from this type of laser system in the near future. Furthermore, similar high-quality pulse trains with shorter wavelengths in the center of the second telecom window might be accessible with this approach using different neodymium doped gain materials.

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