

# 4 W continuous-wave narrow-linewidth tunable solid-state laser source at 546 nm by externally frequency doubling a ytterbium-doped single-mode fiber laser system

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**Abstract:** A high-power continuous-wave coherent light source at 545.5 nm is described. We use 8.3 W from a solid-state ytterbium-doped single-mode fiber oscillator/amplifier system as input into an external frequency doubling stage. This system produces up to 4.1 W of stable green single-frequency laser radiation. We characterize the light source by performing absorption spectroscopy on iodine across the full tuning range of the fiber laser and saturation spectroscopy on one strong iodine line of the doppler-broadened spectrum.

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**OCIS codes:** (140.7300) Visible lasers; (190.7070) Two-wave mixing; (300.6550) Spectroscopy, visible

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## 1. Introduction

Since their invention in 1962 [1], ytterbium-doped fiber lasers have become powerful tools. A three-level transition of Yb<sup>3+</sup> lases at 974 nm, and a four-level transition enables tunable operation between 1010 nm and 1162 nm [2]. Continuous-wave powers of 1.36 kW [3] and pulsed peak powers of 175 kW [4] have been demonstrated. Pulses as short as 36 fs have been produced [5]. One important application of ytterbium fiber lasers in the infrared at 1083 nm is to produce hyperpolarized <sup>3</sup>He by optical exchange pumping [6, 7, 8]. Laser radiation from fiber lasers can also be converted to the visible or even the ultraviolet region by frequency doubling and frequency quadrupling, respectively [9]. Using a periodically-poled MgO crystal, a continuous-wave ytterbium fiber laser has been frequency doubled to do sub-doppler spectroscopy on molecular iodine, measuring the absolute frequency of the hyperfine components of a line at 514.7 nm [10]. Sub-doppler spectroscopy of molecular iodine has also been done at 541 nm with a laser system based on a diode laser, that was amplified by a ytterbium fiber amplifier and frequency doubled by a periodically-poled KTiOPO<sub>4</sub> crystal [11].

In this paper, we describe a high-power laser system at 545.5 nm based on a high-power ytterbium fiber laser system with external frequency doubling. This system has been developed for a continuous-wave Lyman- $\alpha$  source which is based on four-wave sum-frequency mixing of laserbeams at 254 nm, 408 nm, and 546 nm wavelength in mercury vapor [12]. A next-generation Lyman- $\alpha$  source will be based on high-power solid-state laser systems, and a 750 mW system at 253.7 nm has been described already [13].

The laser source and the frequency doubling setup are described in section 2, in which we emphasize details that are important for obtaining stable high output powers and high conversion efficiencies. In section 3 we present absorption and sub-doppler spectroscopy on molecular iodine.

## 2. The setup

Figure 1 shows a diagram of both, the laser system and the iodine spectroscopy setup. The laser consists of three components. The first, a ytterbium-doped fiber oscillator (Koheras Adjustic Model RTAdY10PztS), generates an output power up to 127 mW with a linewidth of 60 kHz. It is tunable from 1090.81 nm to 1091.19 nm by changing the temperature of the lasing fiber. For fast modulation it is tunable for an additional 8.4 GHz by applying a voltage to a piezo that stretches the fiber. The second component, a ytterbium-doped preamplifier (Koheras Boostik Model BoY10Amp), compensates for losses introduced after the oscillator. The third component a ytterbium-doped high-power amplifier (Koheras Boostik Model BoY10Amp), boosts light from a minimum input power of 90 mW to a maximum of 9.3 W. All three fiber laser components use single mode fibers. The frequency doubling stage is a modified

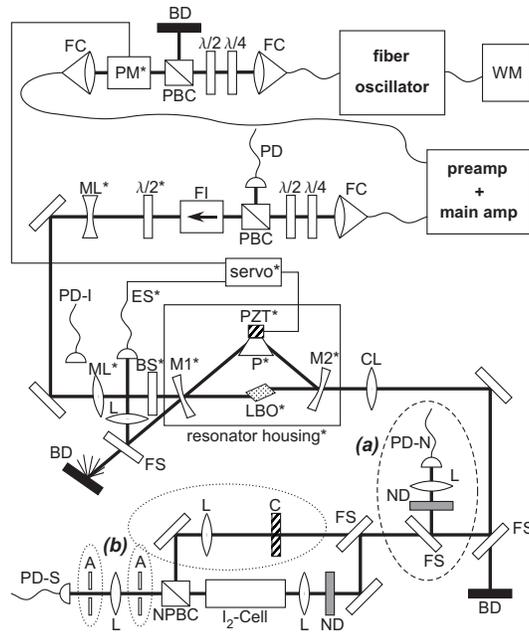


Fig. 1. Experimental setup. WM, wavelength meter; FC, fiber collimator;  $\lambda/4$ ,  $\lambda/2$ , wave plates; PBC, NPBC, polarizing and non-polarizing beam splitter cubes; BD, beam dump; PM, phase modulator; PD, PD-I, PD-N, PD-S, photodiodes; FI, faraday isolator; ML, mode matching lens; BS, beam shifter; FS, fused silica window; L, CL, lenses; ES, unit for error signal detection; M1, M2, cavity mirrors; LBO, lithium triborate crystal; P, prism; PZT, piezoelectric transducer; ND, neutral density filter; C, chopper; A, aperture. Part (a) is used to normalize the absorption-spectroscopy signal, and part (b) is used for doppler-free saturation spectroscopy.

commercial setup (Spectra-Physics WaveTrain [14]) stabilized by the Pound-Drever-Hall locking technique [15]. The resonator consists of a Brewster-cut lithium triborate (LBO) crystal, a curved incoupling mirror M1, a curved outcoupling mirror M2, and a fused silica prism mounted onto a piezo. The whole resonator is assembled inside an aluminum housing with windows for the laser beams. It can be covered by a lid and is then sealed against dust and convection. In addition that housing attenuates acoustical disturbances and external thermal fluctuations. The crystal is type I phase matched by angle tuning. Its temperature is held constant at 308 K using a peltier element placed beneath the crystal that stabilizes the temperature-dependent phase matching angle and prevents condensation of atmospheric water vapor on its surfaces. The prism, which is also used at Brewster's angle, serves two purposes: to redirect the fundamental beam reflected from the outcoupling mirror onto the incoupling mirror, thereby closing the ring cavity, and to scan and stabilize the cavity. This triangular resonator design [14] makes it possible to construct, in contrast to the common bow-tie design for frequency doubling resonators [16], a rather small cavity with a short optical roundtrip path length of  $< 20$  cm. A short cavity leads to additional intrinsic locking stability for two reasons. First, a short path length makes the cavity alignment less susceptible to beam pointing due to disturbances of the optical elements. Second, the cavity linewidth is larger for a shorter cavity at the same finesse. This makes locking the cavity to the fundamental wavelength less sensitive to changes of the effective cavity length caused by vibrations of cavity elements. In our setup, the ellipticity of the frequency doubled beam is 0.8. The beam is collimated by a

single 155 mm lens CL. From the maximum fiber laser output power of 9.3 W, 8.3 W remain after the faraday isolator. Using this fundamental radiation as input into the cavity, an output power of 4.1 W at 545.5 nm is produced.

The commercial frequency doubling system is not designed for multi-watt input power levels. For this reason and also to reach optimum conversion efficiencies, we modified the commercial system. Components, that are part of the original WaveTrain package, are marked with an asterisk in Fig. 1. The infrared input power is higher than the damage threshold of the phase modulator used for generating the sidebands for the error signal. The phase modulator is therefore inserted between the fiber oscillator and the fiber power amplifiers. For precise adjustment, we placed the first mode matching lens on a linear translation stage, as the second lens is. The second lens is slightly tilted ( $7.5^\circ$ ) to adjust the incoming beam to the ellipticity of the beam inside the cavity. Since the error signal detection unit ES would be damaged by our high input power, only the fraction of the beam reflected by the incoupling mirror that is also reflected by an additional fused silica window is directed onto this unit. The transmitted part of the beam is sent onto a beam dump. Some of the stray light is detected by an additional photodiode in order to monitor the incoupling efficiency into the cavity. For optimal phase matching and thereby maximum output power of the cavity, the crystal angle  $\varphi$  has to be adjusted according to the input wavelength and crystal temperature. At low input powers, this can be done by removing the incoupling mirror from the cavity and adjusting the crystal angle in single pass, undisturbed by intensity changes of the enhanced fundamental light due to cavity alignment. After replacing the input coupler, the cavity mirrors should be aligned for the cavity mode to match the incoming beam. For high input powers, this method does not render optimal results but is used only to find a starting value for the crystal angle alignment. Due to linear absorption in the crystal the upper side of the crystal holder heats up from 304 K to 315 K at maximum input power. While the crystal temperature rises, the second harmonic power drops from 4.3 W to 1.3 W. To compensate for the higher temperature, the crystal is tilted to lower angles  $\varphi$  to accomplish optimal phase matching. We find that the resonator remains locked while the crystal angle is tuned if the cavity is realigned after each tuning step. Long-term stability at high powers requires permanent removal of the lid of the aluminum housing so that heat generated in the crystal is sufficiently transported away via convection. Figure 2 shows the green output power as a function of the infrared input power. Measurements done with the crystal aligned for maximal single pass conversion efficiency are plotted as circles. Filled circles indicate stable output powers. Open circles show the harmonic power

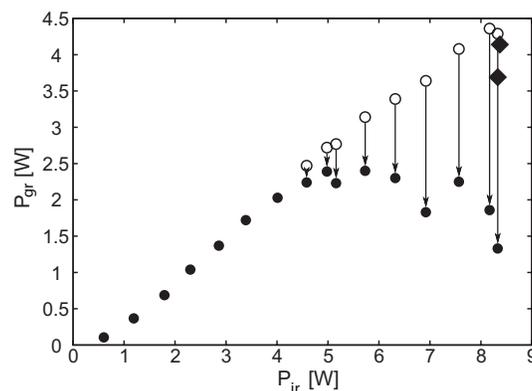


Fig. 2. Green output power  $P_{gr}$  at 545.5 nm as a function of the infrared input power  $P_{ir}$  at 1091 nm.

directly after locking the cavity at one particular input power. The arrows indicate the relaxation to stable output power levels after several minutes of locked cavity operation. Diamonds in Fig. 2 show stable high-power green output at full infrared input power, achieved by using the alignment procedure outlined above. The high-power output is stable for more than 45 minutes.

### 3. Spectroscopy on iodine

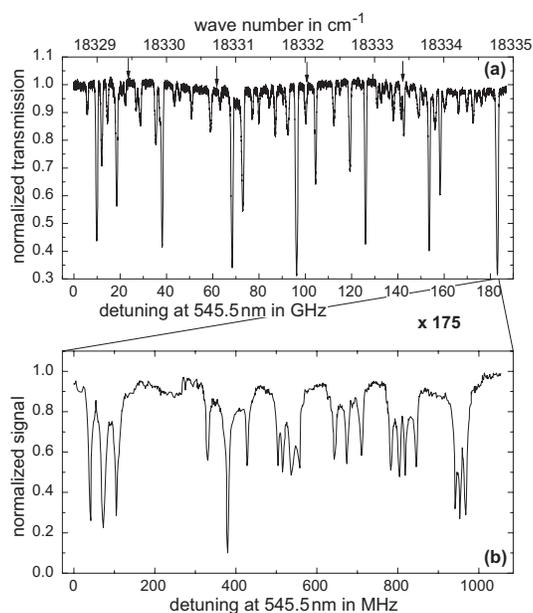


Fig. 3. (a) Absorption spectrum of molecular iodine. (b) Doppler free spectrum of the line at  $18334.8 \text{ cm}^{-1}$

The radiation at 545.5 nm is used for spectroscopy on iodine to demonstrate both, smooth tuning characteristics and single-frequency operation. The spectroscopy part of the setup is shown at the bottom of Fig. 1. We use a cell with a 49 cm column length of iodine vapor at a temperature of 269 K. The absorption signal is measured by photodiode PD-S. The wavelength of the fundamental beam is monitored by a commercial wavelength meter (HighFinesse WS7). The upper scan in Fig. 3 shows a part of the absorption spectrum of the  $X^1\Sigma_g^+ - B^3\Pi_{0g^-}$  electronic transition in molecular iodine vapor [17]. This scan covers the full range of the fiber laser oscillator which involves temperature tuning from 293.0 K to 323.7 K. The doppler-broadened absorption data has been normalized by using the signal from photodiode PD-N. This removes distortions of the spectrum due to fluctuations of the green power. The modulation of the baseline that is left on the data is due to interferences in the windows of the iodine cell. Small arrows above the baseline in the plot mark where the cavity ran out of its tuning range and had to be relocked.

The lower part of Fig. 3 shows doppler-free saturation spectroscopy of the strong iodine line to the right of the doppler-broadened absorption spectrum in part (a). This line is number 4489 in the iodine atlas [17]. For this scan, the wavelength was tuned using the piezo of the fiber laser. Since the wavelength data from the wavelength meter showed unphysical steps below the specified accuracy of 27 MHz at 1091 nm, they were smoothed over five data

points using binomial weighting. For saturation spectroscopy [18], a chopped pump beam counter-propagating with respect to the probe beam is sent through the slightly inclined iodine cell. Two apertures in front of PD-S were used to block out pump light reflected by the window of the iodine cell. The measured signal is rectified using a lock-in amplifier. Figure 3(b) demonstrates that scanning with a frequency doubled high-power ytterbium fiber laser is possible. The linewidth of the laser radiation has not been measured directly in the work presented here. The manufacturer specifies a linewidth of 60 kHz for the fiber laser emission, and we estimate the linewidth of the green light is twice as large.

#### **4. Conclusion**

High-power narrow-linewidth tunable green continuous-wave coherent radiation is produced by using a ytterbium fiber laser and a commercial frequency doubling system. We modified the ring frequency doubling cavity for high input powers and high conversion efficiencies. Stable output powers of 4.1 W at 545.5 nm are generated. Tuning and scanning of the generated radiation has been demonstrated by spectroscopy of molecular iodine. This laser system will enhance our fundamental input power for the generation of Lyman- $\alpha$  by four-wave sum-frequency mixing in mercury vapor.