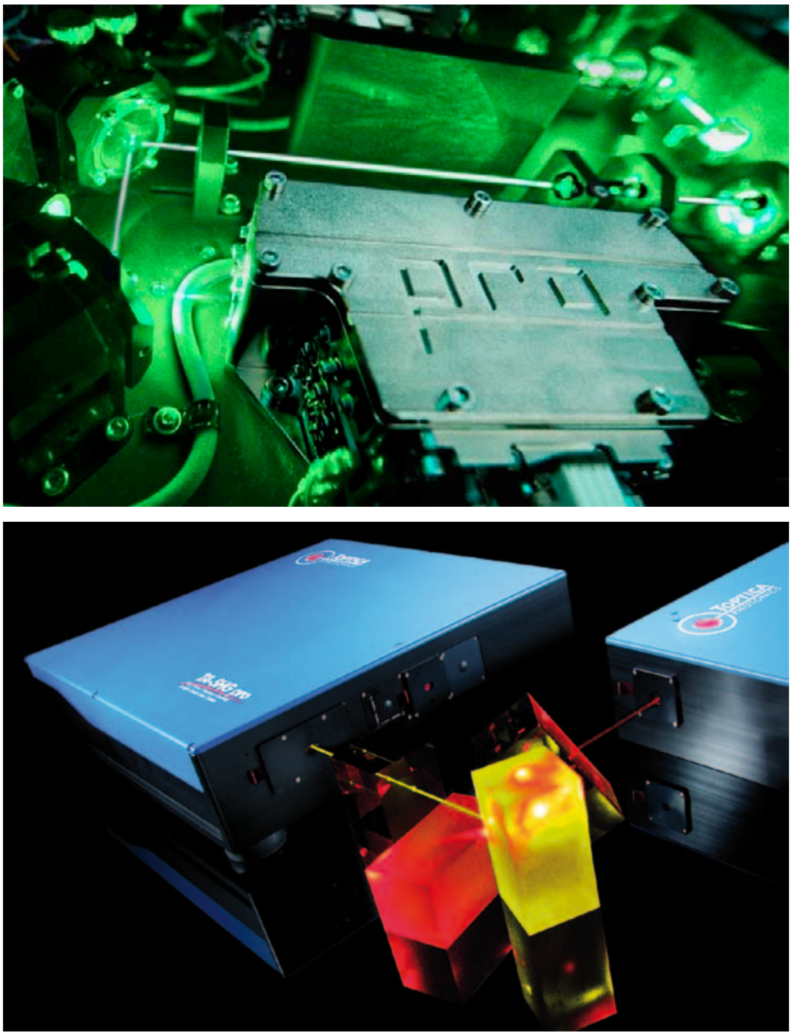
More colors!

Diode lasers reach Yellow and Orange.

Thomas Heine

New developments in semiconductor amplifier and frequency-doubling technology expand the color and power spectrum of tunable diode lasers to more than 1000 mW at yellow and orange wavelengths. Applications such as laser cooling of Sodium, Dysprosium or Erbium and spectroscopy of rare-earth ions in solids benefit from the compact and easy-to-handle laser systems.



Two TA-SHG pro systems generate high output powers at 589 nm and 626 nm (above). The detailed view of the resonant frequency-doubling cavity (is shown below)

Semiconductor lasers enabled the remarkable growth the academic field of spectroscopy, laser cooling and trapping of ions and atoms experienced over the last years. External-cavity diode lasers reliably provide tunable, narrow-linewidth laser radiation for experiments getting more and more complex, most of which involve several laser systems operating simultaneously.

Though diode lasers are available over broad wavelength ranges from the UV to the Infrared, the needs of certain applications cannot be addressed directly. Such wavelength gaps however can be closed by second harmonic generation (SHG) techniques using appropriate nonlinear crystals. Resonant enhancement cavities strongly increase the efficiency of frequency doubling. Recently, tapered semiconductor amplifiers (TA) became available that provide high fundamental powers for SHG to the yellow and orange spectral range. Thus the required power levels for applications such as laser cooling of Sodium, Dysprosium or Erbium and spectroscopy of rare-earth ions in solids can be achieved.

Laser system setup

In this article two similar frequency-doubled diode lasers at 589 nm and 626 nm – for laser cooling of Sodium and Dysprosium – are presented exemplarily. The setup of these commercially available TA-SHG pro systems from Toptica Photonics AG comprises three main components, schematically shown in **Figure 1**.

The master laser DL pro is the centerpiece of the complete system as it provides most of the fundamental properties. Due to its sophisticated opto-mechanical design, the DL pro offers narrow linewidth and a large continuous i. e. mode-hop-free tuning range together with excellent acoustic and thermal stability. In combination with a very low-noise current driver the master laser exhibits a typical short-term linewidth well below 50 kHz. The DL pro can be continuously tuned over 20 GHz using a piezo element together with a system of robust flexures. Using AR-coated laser diodes allows for a coarse tuning over 50 nm and an output power of 100 mW at both fundamental wavelengths.

The recently developed tapered semiconductor amplifiers boost the output power level of the seed laser while maintaining its spectral properties. To prevent the master from disturbing optical feedback, DL pro

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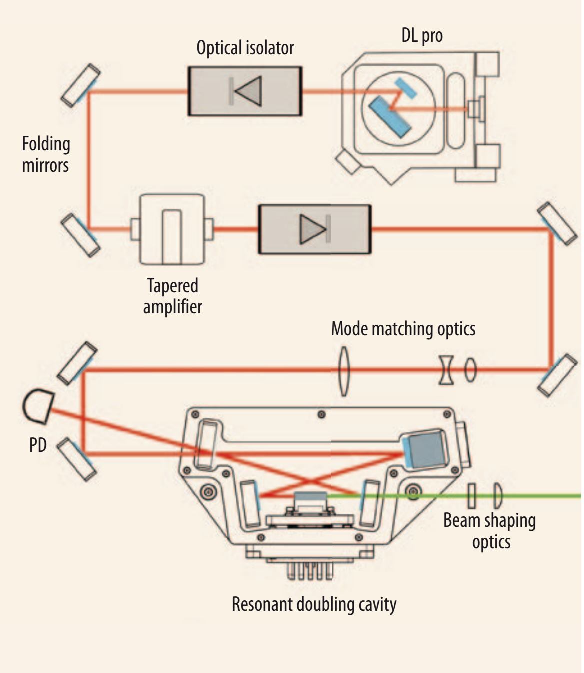

Fig. 1 Schematic of the optical path within a TA-SHG pro: The master laser (DL pro) seeds a tapered amplifier chip. The high power output is then coupled into a resonant doubling cavity that contains the temperature stabilized nonlinear crystal.

and TA are separated by a −60 dB optical isolator. Selected amplifier chips provide an output power of around 2200 mW at 1178 nm and 1252 nm at an applied current of 7000 mA. The coarse tuning ranges of the amplifiers are 1155 to 1190 nm and 1225 to 1275 nm, respectively.

The amplified beam is spatially mode-matched to the enhancement cavity and coupled into it using proprietary mirror mounts based on flexure technology. To generate 589 nm and 626 nm radiation, AR-coated Lithium Triborate (LBO) crystals are used to achieve best frequency doubling efficiencies and good long-term stability. The length of the air-sealed cavity is actively stabilized to the fundamental laser by means of the Pound-Drever-Hall locking scheme. This allows for highly stable locking of the cavity and thus a reliable intra-cavity enhancement of the fundamental light. One of the cavity mirrors is mounted onto a stack of piezo elements forming the actuator of the locking circuit. In order to achieve a wide continuous tuning range, the piezo element offers a large displacement to adjust the cavity length to the actual laser frequency. A second, fast locking circuit acting onto the same stack with bandwidth > 20 kHz compensates for acoustical disturbances impacting the cavity. In a first step the transmission of the incoupling mirror is selected and tested for best impedance matching i.e. to counterbalance both the desired conversion as well as other losses in the cavity. Then, for optimum long-term stability of the system, the transmission of the incoupling mirror is further increased to counterbalance potential additional losses in the cavity by an improved impedance matching.

Lab Results

The TA-SHG pro system at 589 nm provided a maximum output power of 1370 mW, starting from a fundamental power of 2250 mW. This corresponds to a conversion efficiency of 61 %. The above mentioned impedance matching as well as the spatial mode matching of the TA beam to the enhancement cavity strongly affects this overall efficiency as only part of the fundamental light is coupled into the resonator.

For the 626 nm laser system, the second harmonic power versus fundamental power is shown in **Figure 2**. A maximum output power of 1230 mW at 626 nm was reached with 2250 mW of fundamental power. The frequency doubling efficiency of 52 % can potentially be further improved by optimizing the spatial mode matching.

For both systems the laser frequency can be continuously tuned over a range of 40 GHz. This corresponds to a wavelength change of 0,05 nm, which is sufficient to cover the relevant spectral lines of Sodium or Dysprosium.

If the wavelength of the master laser is coarsely shifted the phase matching between fundamental and second harmonic wave has to be optimized again in order to reach maximum output power. A coarse tuning range of 10 nm of the second harmonic output was achieved by just using the temperature of the nonlinear crystal for phase adjustments.

Diode lasers exhibit lower intensity noise figures compared to other types of lasers, only marginally raised by the resonant second harmonic generation. The relative intensity noise spectrum of the frequency-doubled diode laser at 626 nm is shown in **Figure 3**. It was recorded in an office like environment and the

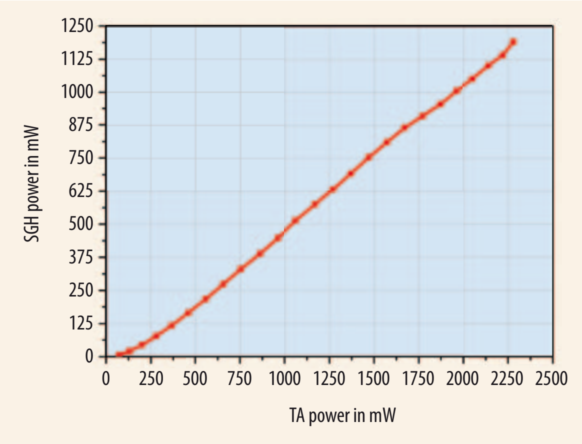

Fig. 2 Harmonic output power versus fundamental power for the TA-SHG pro at 626 nm

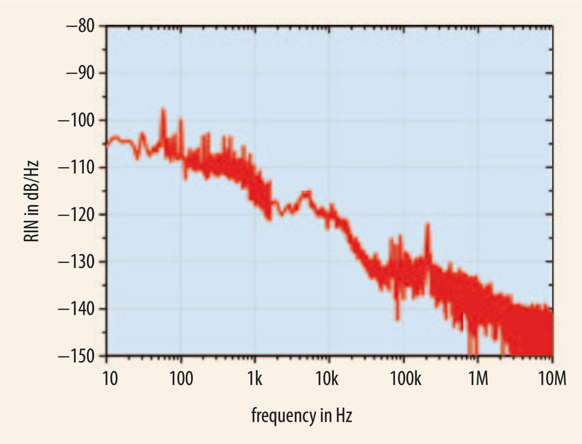

Fig. 3 Relative intensity noise (RIN) spectrum of the TA-SHG pro laser at 626 nm

master laser was neither frequency stabilized nor linewidth narrowed.

Long-term measurements of the frequency-doubled output showed a very low power variation over a period of 16 days as illustrated in **Figure 4**. This remarkable stability was achieved by a laser head machined from a solid metal block, the flexure based mirror mounts, the opto-mechanical design of the maser laser and the air-sealed frequency-doubling cavity itself. Losses in output power could have been recovered by simple readjustments of the incoupling mirrors.

Conclusion and Outlook

Based on tapered semiconductor amplifiers two compact frequency-doubled, tunable laser systems were realized, with a power of more than 1000 mW at 589 nm and 626 nm, low intensity noise and excellent longterm stability. High output powers at manifold other wavelengths not available by direct diode lasers can be addressed using a similar setup but different semiconductors, mirror coatings and doubling crystals. In addition to the second-harmonic generation scheme described here, two frequency doubling stages can be cascaded to achieve fourth-harmonic generation (FHG) directing into the deep UV.

Almost 15 years ago, Toptica Photonics AG started developing SHG and FHG diode lasers. More than 250 systems were already assembled within a wavelength range from 190 nm to 635 nm. The know-how accumulated is constantly fed back into the development and optimization of the systems to reach new wavelengths, increase performance and ease of use.

Our novel approach for a guide star laser impressively shows the potential and reliability of resonant second harmonic generation. The 20 W laser system will be installed directly in the structure of next-generation astronomical telescopes and is designed to excite sodium atoms in the Earth's mesosphere at an altitude of 90 km. It will act as an artificial star enabling adaptive optics to correct for wavefront distortions induced by turbulence in the Earth's atmosphere.

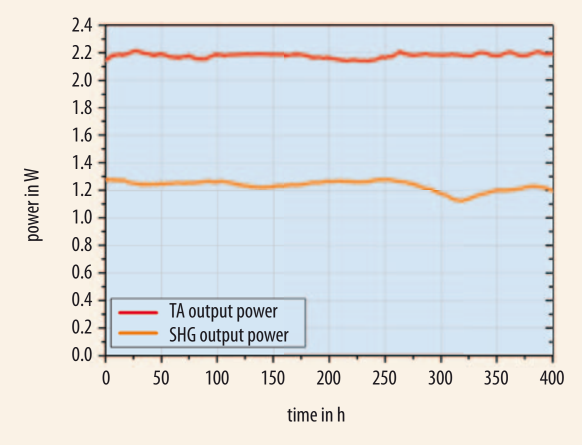

Fig. 4 Long-term output power stability of the TA-SHG pro at 589 nm measured over a period of 400 h (16 days). The red line shows the fundamental power (TA), the yellow line depicts the output power after frequency doubling.