Highly efficient cw frequency doubling of 854 nm GaAlAs diode lasers in an external ring cavity

O.S. Brozek [a,b,1], V. Quetschke [b], A. Wicht [b], K. Danzmann [a,b]

[a] Max-Planck-Institut für Quantenoptik, Außenstelle Hannover, Callinstrasse 38, 30167 Hannover, Germany
[b] Institut für Atom- und Molekülphysik, Abteilung Spektroskopie, Universität Hannover, Callinstrasse 38, 30167 Hannover, Germany

Abstract

We report on 50% conversion efficiency for frequency doubling of a 854 nm GaAlAs diode laser using a potassium niobate crystal in an external ring cavity. Frequency stabilization of the diode laser is achieved by direct optical feedback from the doubling cavity or from a grating in Littrow configuration. We determine 200 kHz linewidth from the measured spectral density of the frequency noise and from a beat signal measurement of two independent diode lasers. The blue output power of 7.8 mW shows rms-fluctuations of less than 0.6% in 1 MHz bandwidth. © 1998 Elsevier Science B.V.

1. Introduction

We present frequency and intensity noise measurements of a cw all-solid-state laser system to be used in the realization of negative dispersion without absorption [1] on the $^1S_0 \rightarrow {}^1P_1$ transition of ^{40}Ca at 423 nm. This atomic transition is also used for laser cooling of calcium atoms in the context of a compact and transportable calcium atomic clock [2]. Apart from spectroscopy there is strong interest in blue laser systems for optical data storage and colour display techniques. Despite recent encouraging results in the development of light emitting diodes and laser diodes emitting in the blue region of the spectrum [3] it is not clear when these devices will fulfill the spectral requirements needed in high resolution cw spectroscopy. We set up a compact and highly efficient all-solid-state laser system, which features high stability in frequency and

amplitude and provides output powers of several tens of mW.

Resonant frequency doubling of GaAlAs diode lasers with a wavelength of about 850 nm using potassium niobate ($KNbO_3$) as a nonlinear crystal allows stable single frequency operation and rather high conversion efficiencies even for laser diodes with output powers of only a few tens of mW. In particular, monolithic doubling cavities provide good stability. Conversion efficiencies up to 48% for a $KNbO_3$ monolithic cavity at 429 nm [4] and of up to 89% for a $MgO:LiNbO_3$ semimonolithic cavity at 532 nm [5] have been reported. Nevertheless, frequency tuning of monolithic $KNbO_3$ doubling cavities is complicated. In addition, the crystal may no longer be used when a crystal defect is located at the optical axis. A discrete non-monolithic setup allows the variation of all system parameters in order to achieve highest conversion efficiencies. Therefore, we have decided to use an external ring cavity in bow-tie configuration as resonator [6,7] for the frequency doubling of our GaAlAs laser diodes.

[1] E-mail: brozek@mpq.mpg.de.

2. Experimental setup

An a-cut potassium niobate crystal used for frequency doubling enables 90° type I-noncritical phasematching between 840 and 940 nm [9,10]. The nonlinear-optical d_{32}-coefficient has a value of 20.5 pm/V [10,11]. For the generation of 423 nm radiation the crystal has to be cooled to the phasematching temperature of approximately −13°C. For our first experiments we used a fundamental wavelength of 854 nm to ease the cooling problem. A phasematching temperature of about +12°C could be used in this case. Two different diode laser setups for the frequency stabilization were investigated. Frequency stabilization and locking of the diode laser to the doubling cavity can be achieved by direct optical feedback from the doubling cavity [7] (Hollberg system). This simple and practical setup allows high injection currents and thus high output powers but stable operation can be distorted by too much optical feedback. Another method for the stabilization and reduction of the frequency noise of a free running diode laser is to use the optical feedback from an external grating (grating laser system). This gives moderate optical output power, but features a high tuning range of more than 15 nm.

The experimental setup for the grating laser system is shown in Fig. 1. The radiation of an AR-coated, cw GaAlAs laser diode (SDL5410-C, maximum rating: 100 mW for 120 mA injection current) with a front facet reflectivity of $R < 5 \times 10^{-3}$ is collimated by an AR-coated focusing lens ($f = 4.5$ mm, 0.55 NA) and stabilized by the optical feedback from a holographically fabricated optical grating [12] with 1400 lines/mm and a diffraction efficiency of $R \approx 25\%$. The grating is mounted onto a piezo electric transducer (PZT). By applying a voltage to the PZT the grating laser can be continuously fine tuned within a tuning range of more than 30 GHz at a slope of 0.5 GHz/V. The diode laser setup is temperature stabilized by an active Peltier cooling setup to short term temperature fluctuations $\Delta T < 10$ mK. We reduce the maximum injection current to 50 mA in order to avoid catastrophic optical damage (COD) of the laser diode's mirrors. The ellipticity of the transversal mode of the diode laser is 1:3. An anamorphic prism pair AR-coated for the

fundamental wavelength is used in order to reduce the ellipticity of the laser field for optimum mode matching to the doubling cavity. Mode matching and beam steering is done by fine adjustment of the two curved mirrors. A Faraday isolator with 60 dB extinction ratio is placed between the laser system and the doubling cavity to minimize optical feedback.

The ring cavity in bow-tie configuration is formed by four mirrors with a folding angle as small as possible in order to minimize the astigmatism; here we have a full angle of about 12 degrees. The plane mirror M1 has a transmission T_1 and the second surface is AR-coated for the fundamental wavelength; the optimum transmission T_1^{opt} to achieve impedance matching is given by [14]:

$$T_1^{opt} = \mathscr{L}/2 + \sqrt{\mathscr{L}^2/4 + \eta P_1} . \tag{1}$$

The optimum transmission depends on the nonlinear conversion loss due to harmonic generation ηP_1 and on the linear losses $\mathscr{L}$ of the resonator and the crystal. We use several mirrors for input coupling with a transmission range T_1 from 1.0% to 8.0% in order to couple a maximum amount of the fundamental power into the cavity.

The plane mirror M2 is mounted on a fast PZT for scanning the cavity or locking it to the laser frequency. The error signal for locking the cavity to the laser frequency is derived by a polarization spectroscopy scheme introduced by Hänsch and Couillaud [13]. The light reflected from the doubling cavity is split into left and right circular polarized light by means of a quarter-wave plate and a polarizing beam splitter and is detected by two photodiodes. The 3 dB-bandwidth of the photodiodes and of the error signal electronics is 200 kHz. The mirrors M3 and M4 each have a curvature of 50 mm and a separation L of 57.5 mm. The total cavity length is about 500 mm resulting in a free spectral range of 600 MHz. The mirror M4 has high transmission for 427 nm. This mirror substrate is formed as a meniscus lens with $f = 25$ mm, so that the blue light passing through the mirror is already collimated. The reflectivity of the mirrors M2, M3 and M4 at 854 nm is better than 99.9%.

The crystal is centered around the smaller focus between the two curved mirrors. The beam waist radius w_0^1 is
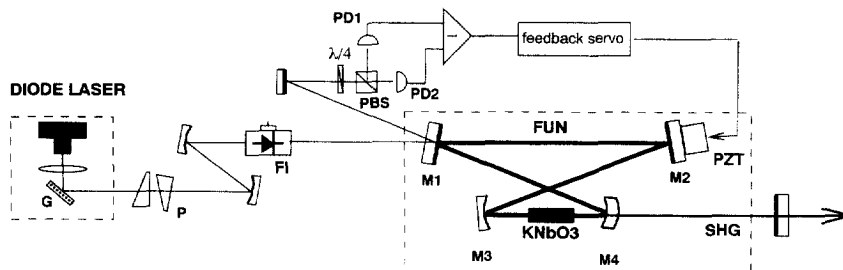

Fig. 1. Schematic diagram of the frequency doubling setup. G, grating; P, anamorphic prism pair; FI, Faraday isolator; PZT, piezo electric transducer; λ/4, quarter-wave plate; PBS, polarizing beam splitter; PD1, photo diode 1; PD2, photo diode 2; FUN, fundamental field, SHG second harmonic field.

19 μm. The second beam waist has a radius of $w_0^{II} = 225$ μm as calculated from the resonator geometry. The fundamental light is focused by means of the mirror telescope in front of the cavity and via a small displacement of the two mirrors the beam waist of the fundamental field can be changed in order to adjust the mode matching. The nonlinear $KNbO_3$ crystal has a length of 9 mm and is AR-coated for the fundamental ($R < 0.4\%$) and for the harmonic ($R < 0.5\%$). The total transmission loss introduced by the crystal was determined in a single pass measurement to be 1.16%, indicating an absorption coefficient of 0.3–0.4%/cm at 854 nm. These values are slightly higher than those specified by the manufacturer [11]. The absorption coefficient for the harmonic wavelength is expected to be higher, because of an absorption edge at 400 nm [9,15]. The whole resonator is mounted on a massive block of brass and enclosed in a metal box. The crystal is mounted on a Peltier element to allow temperature tuning. In order to achieve good heat conductivity the crystal is wrapped into a thin indium foil of 50 μm thickness. The crystal housing is placed on an adjustable tilt mount in order to align the crystal axis independently from the doubling cavity. A small amount of nitrogen with a rate of less than 5 l/h is blown through the crystal housing to avoid damage of the potassium niobate crystal by dust and humidity.

The optimum beam parameter for frequency doubling with Gaussian beams is given by the Boyd-Kleinman theory [16]: $b_0/L_c = 2.84$. Here $b_0 = 2\pi n w_0^2 \lambda$ is the confocal parameter, w_0 the beam waist radius inside the crystal, λ the wavelength, n the index of refraction and L_c the crystal length. For a 9 mm long crystal the optimum beam waist w_0^{opt} is 14 μm. We decided to use a beam waist of 19 μm, resulting in a 12% lower nonlinear coefficient $\eta = P_2/P_1^2$ in order to reduce the resonator length for practical handling. Here P_1 is the fundamental power and P_2 the converted second harmonic power. The theoretical value for η is 7.3%/W for a 9 mm long crystal and optimum focusing. In a single pass measurement we have produced 110 μW of blue light with a fundamental power of 60 mW, indicating a normalized conversion efficiency of $\eta = 2.5\%$/W. This discrepancy has also been observed by other authors [7] and is possibly due to a lower nonlinear-optical coefficient d_{32} than 20 pm/V [8]. Other effects reducing the macroscopic nonlinear coefficient η are temperature effects and inhomogeneities in the crystal resulting in non-optimum phase matching [15].

3. Hollberg laser setup

In a first experiment we set up a free running laser diode without grating feedback providing 70 mW of fundamental power in front of the doubling cavity. Optical feedback from the counterpropagating mode of the ring resonator locks the laser to the cavity [5]. With this setup

we achieved 35 mW of cw blue radiation at 427 nm, which corresponds to a conversion efficiency $\epsilon = P_2/P_1$ of 50%. This harmonic output power is a factor of 5 higher than that reported by Hemmerich et al. [7]. Taking into account the loss of 20% due to nonperfect mode matching, this gives an internal doubling efficiency of 62%, which is in good agreement with the calculated value using a nonlinear coefficient of 2.5%/W. For these values only the harmonic transmission loss of 8% of the outcoupling mirror was taken into account.

However, it was very difficult to achieve stable operation. This laser system showed multimode and chaotic effects [17] due to too much optical feedback from the doubling cavity, which turned out to be extremely sensitive to the alignment of the setup. Up to 2 mW of fundamental power was typically directed back to the diode laser. Please note, that due to the good modematching almost all of this power was coupled back into the laser diode! Therefore, stable operation could not be achieved without an optical isolator which was slightly detuned from optimum isolation to provide a very small amount of optical feedback.

4. Grating laser setup

Due to the problems of the Hollberg laser system mentioned above we set up a grating laser which was optically decoupled from the doubling cavity. In addition, this setup has the advantage of a large wavelength tuning range. With the grating laser setup described in Fig. 1, we achieved up to 7.8 mW of blue light at a wavelength of 427 nm with 22 mW of fundamental power measured in front of the doubling cavity. Stable operation is possible for hours, only interrupted by a strong mechanical or electrical disturbance. Within 1 hour we have measured a maximum deviation from the average blue power of 0.5%. We have determined the conversion efficiencies at different fundamental powers of the grating laser system in order to experimentally check the system parameters given by the manufacturer or calculated from theory. The theoretical efficiency ϵ is given by [6]:

$$\epsilon = \frac{\eta \, m P_1 \, T_1^2}{\left\{ 1 - \sqrt{1 - T_1} \, \sqrt{1 - \mathscr{L}} \left(1 - \sqrt{\eta \epsilon \, m P_1} \right) \right\}^4} \, . \quad (2)$$

Here η is the nonlinear coefficient, m is the loss factor due to nonperfect mode matching, P_1 the fundamental power, T_1 the transmission of the input coupling mirror, and $\mathscr{L}$ the linear resonator losses resulting from absorption, scattering, the reflectivity of the AR-coatings of the crystal and the transmission of the cavity mirrors. We determined the linear loss $\mathscr{L}$ to be 1.6%, the nonlinear coefficient η to be 2.5%/W, the transmission of T_1 to be 2.1% and the mode matched input factor m to be 0.8. In Fig. 2a, 2b the measured and calculated harmonic powers P_2 and conver-
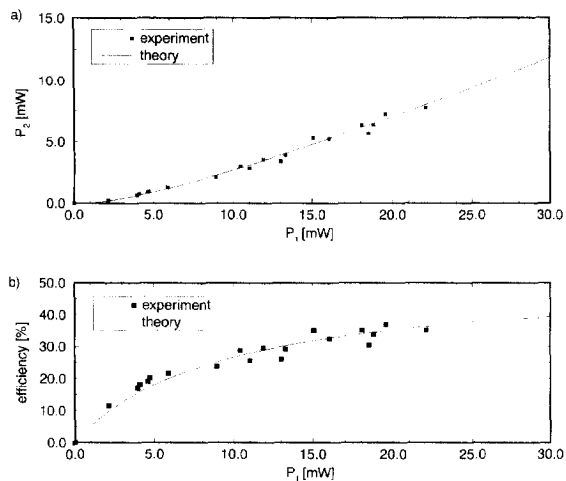
Fig. 2. Measured second harmonic power P_2 (a) and conversion efficiency (b). The theoretical value is given by the solid line; it is derived from Eq. (2) with $T_1 = 2.1\%$, $\eta = 2.5\%/W$, $m = 0.8$, $\mathscr{L} = 1.6\%$.

sion efficiencies ϵ are shown for different pump powers P_1. For this measurement the laser was scanned over the cavity resonance, and the harmonic power was detected with a calibrated photodiode. It was checked, that thermal effects did not introduce a discrepancy between maximum blue output for the scanned and cw operation. The internal power was determined by the 5×10^{-4} infrared transmission of mirror M3. A power buildup of a factor of 25 and an internal power of 0.55 W have been measured. The normalized conversion efficiency η results in $2.5\%/W$.

This is the same value that has been observed in a nonresonant, single path measurement. Hence, a good agreement between calculated and measured data is found.

To increase the conversion efficiency even further, the linear losses have to be reduced in order to achieve a larger power build up inside the cavity. The optimum length of a nonlinear crystal is achieved when the resonator loss equals the absorption for the fundamental inside the crystal. A longer crystal would allow to reduce the resonator length and the beam radius w_0^{II} inside the crystal. So thermal effects which will become important at higher power levels or shorter wavelengths will be reduced. On the other hand for a longer crystal the phase distortion due to imperfect crystal quality would be increased and hence the power build up inside the cavity would be limited. We think, that a crystal length of about 15 mm is a good compromise and in the future we will use a 15 mm $KNbO_3$ crystal.

5. Noise measurements

In order to characterize the stability of the laser system, we have measured the frequency and the intensity noise. The frequency noise of the fundamental is measured at the error point of the frequency stabilization servo loop and analyzed with an HP3589 spectrum analyzer. Since the measured bandwidth of the servo loop is about 6.6 kHz, the frequency noise for Fourier components above the unity gain frequency represents the frequency variations of the free-running grating laser relative to the doubling cavity. Fig. 3 shows the frequency noise at the error point;
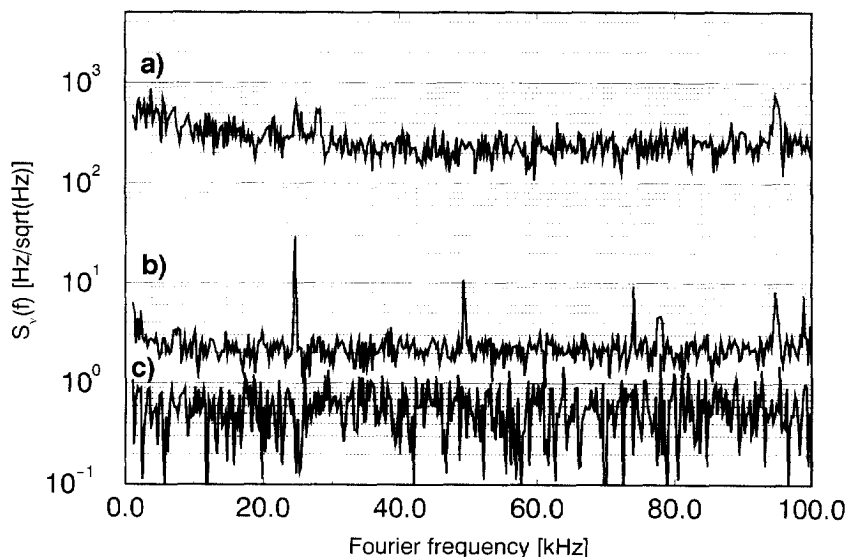

Fig. 3. Linear spectral density of the frequency fluctuations $S_\nu(f)$ of the fundamental field measured at the error point of the frequency stabilization servo loop (a), electronic noise floor (b) and HP3589 input noise (c). The peaks at multiples of 24.5 kHz in the electronic noise curve (c) result from the power supply.

a linear spectral density $S_\nu(f)$ of less than 300 Hz/$\sqrt{\text{Hz}}$ between 1 kHz and 100 kHz has been measured. The reproduceable small peak at 28 kHz is caused by a resonance of the PZT mirror mount. We can estimate the linewidth (FWHM) $\Delta\nu$ of the grating laser assuming white frequency noise with a linear spectral density of 300 Hz/$\sqrt{\text{Hz}}$ [18]:

$$\Delta\nu_{\text{rms}} = \pi S_\nu(f)^2. \tag{3}$$

This results in a linewidth of 280 kHz for the 854 nm grating laser which is in good agreement with a linewidth of 200 kHz obtained in a beat signal measurement (40 μs recording for FFT) of two independent grating lasers. For a measurement of the linewidth of the blue field two independent frequency doubled lasers or a stabilization to an atomic line is needed. This measurement is in preparation. Frequency stabilization of the laser diode setup to the ^{40}Ca transition would reduce the frequency noise and provide a better stability in frequency and intensity of the second harmonic laser field.

The intensity noise of the fundamental and the harmonic field have been measured with an ac-coupled silicon photodiode. Fig. 4 shows the linear spectral density of the relative intensity noise of the grating laser (IR), the infrared field transmitted by the doubling cavity (FUN) and the second harmonic field (SHG). The intensity noise of the grating laser is shot noise limited for a photocurrent of 0.6 mA at Fourier frequencies above 30 kHz. The linear spectral density $S_{\text{RIN}}(f)$ of the relative intensity noise of the grating laser is $2.3 \times 10^{-8}/\sqrt{\text{Hz}}$ and the value for the harmonic field is about $6 \times 10^{-6}/\sqrt{\text{Hz}}$ which is 6 dB above the pump field inside the cavity, as expected in the classical case of large fluctuations compared to the quan-

tum noise. This results in a rms-variation of 0.6% in 1 MHz bandwidth for the blue output. The increase of the relative intensity noise of the harmonic field with respect to the relative intensity noise of the fundamental field by more than 40 dB has yet not been understood. We think this excess noise is due to the frequency noise of the laser diode generating amplitude fluctuations in the doubling cavity. In the case of a small offset Δ between the frequency of the laser diode and the doubling cavity the frequency noise produces to first order a linear spectral density of relative intensity noise which is given by

$$S_{\text{RIN}}(f) = 2\frac{\Delta}{\Gamma}\frac{S_\nu(f)}{\Gamma}, \tag{4}$$

where Γ is the cavity linewidth (HWHM). A frequency noise of 300 Hz/$\sqrt{\text{Hz}}$, an offset of 0.01 of a cavity linewidth and a linewidth of 2 MHz would produce $6 \times 10^{-6}/\sqrt{\text{Hz}}$ of relative intensity noise for the transmitted field. This noise increase is used in order to adjust the cavity offset Δ: we modulate the injection current of the diode laser at a frequency above the unity gain frequency of the frequency stabilization servo loop. This frequency modulation produces a strong signal for the transmitted fundamental and for the harmonic light at the modulation frequency and its harmonic. The cavity offset can then be adjusted by minimizing the modulation signal in the power spectrum.

However, this method did not provide a reduction of the noise power below $4 \times 10^{-6}/\sqrt{\text{Hz}}$ for the transmitted fundamental. Hence to first order the excess noise is not produced by frequency noise. We have also checked, that the power noise spectrum of the diode laser is not affected when the doubling cavity is locked to the laser. Therefore,
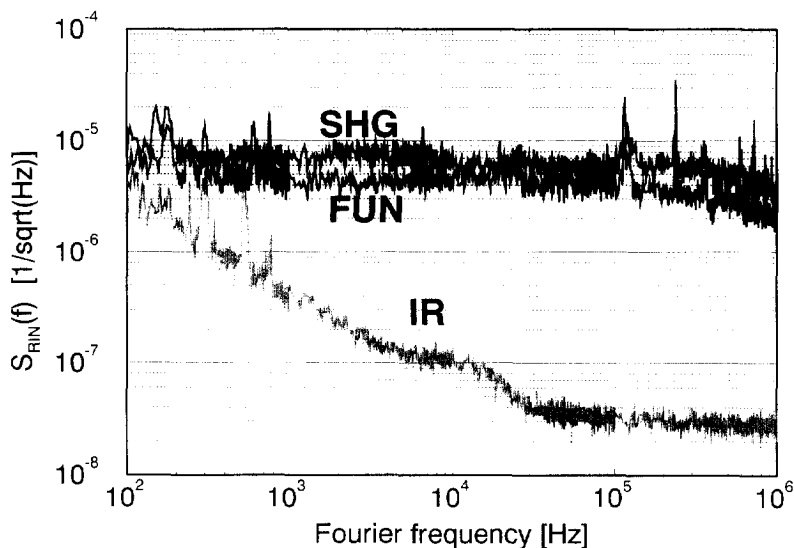

Fig. 4. Linear spectral density $S_{\text{RIN}}(f)$ of the relative intensity noise of the harmonic field (SHG), the fundamental field transmitted by the doubling resonator (FUN) and of the grating laser system (IR).

optical feedback from the doubling cavity is not the origin of the excess noise. Further, the same excess noise is measured when the cavity is operated at a much higher crystal temperature, when an efficient frequency doubling did not affect the intensity noise of the transmitted field.

We think a second order effect is producing this excess noise from frequency fluctuations. Besides this, beam pointing instabilities and mode fluctuation can be an origin of excess noise. An investigation of these effects has to be done in order to achieve a lower intensity noise.

6. Conclusion

In summary we have set up a highly efficient low noise all-solid-state laser system at a wavelength of 427 nm. An optical to optical conversion efficiency of 50% and an internal efficiency of 62% have been obtained with a Hollberg laser setup; 35 mW of blue light have been generated from 70 mW of infrared light in front of the doubling cavity. This conversion efficiency is in good agreement with the calculated values using the experimentally determined parameters of the system.

With a 22 mW grating laser setup up to 7.8 mW of blue light have been produced. The relative intensity noise has been measured to be $6 \times 10^{-6}/\sqrt{\text{Hz}}$ and the frequency noise at the error point of the pump field is measured to be less than $10^3 \text{ Hz}/\sqrt{\text{Hz}}$ for Fourier frequencies above the unity gain of the frequency stabilization servo loop. We have determined the short term linewidth of the free running grating laser setup to be 200 kHz.

Acknowledgements

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