Second-harmonic generation and optical stabilization of a diode laser in an external ring resonator

A. Hemmerich, D. H. McIntyre, C. Zimmermann, and T. W. Hänsch

Max-Planck-Institut für Quantenoptik, D-8046 Garching bei München, Federal Republic of Germany

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The second harmonic of the 842-nm output of a GaAlAs diode laser is generated in a $KNbO_3$ crystal in a resonant, external ring cavity. The diode laser is optically stabilized to the ring cavity through feedback from the counterpropagating fundamental wave, which is weakly excited in the resonator. We have produced 6.7 mW of tunable, narrow-band radiation at 421 nm and have used that light to perform saturation spectroscopy on narrow transitions in rubidium.

Diode lasers provide a compact, efficient, and economic source of coherent radiation. Their broad tuning range also makes them especially well suited for spectroscopy. The use of diode lasers has been limited because they are available only in specific wavelength regions and they generally have a broad spectral linewidth (>20 MHz), which is unsuitable for many precision experiments. However, recent research has shown that diode-laser linewidths can easily be reduced to the 10-kHz level by feedback from an external Fabry–Perot resonator.[1] In addition, recent results in the frequency doubling of diode lasers demonstrate that one can use them as sources of blue or violet light, thus extending their range of usefulness.[2,3] In this Letter we combine these two concepts in a system that produces narrow-bandwidth violet light suitable for high-resolution laser spectroscopy.

Optical stabilization of diode lasers to external resonators relies on the high sensitivity of these lasers to optical feedback. Dahmani *et al.* showed that the weak feedback from a tilted confocal étalon causes the diode laser to lock its own frequency automatically to the cavity resonance.[1] The laser linewidth in their experiment was reduced a thousandfold from 20 MHz to approximately 20 kHz.

Frequency doubling of diode lasers is generally limited by the low power available from single-mode lasers. However, by combination of the high nonlinearity of potassium niobate ($KNbO_3$) with the technique of resonant enhancement of the fundamental power, good second-harmonic efficiency is possible. Dixon *et al.* were able to generate 0.215 mW of 432-nm second harmonic with 12.4 mW of fundamental input power in a linear enhancement cavity.[3] They also employed the method of optical stabilization, although they had to use a Faraday isolator to avoid direct reflection from the linear cavity and then redirect the output of the cavity back to the laser to obtain the necessary optical feedback.

We report here on the generation of tunable, narrow-bandwidth 421-nm radiation by the frequency doubling of a 842-nm diode laser in a $KNbO_3$ crystal in an external ring resonator. The diode laser is optically stabilized to the external ring cavity by use of a novel scheme for optical feedback. This feedback is obtained from the weakly excited counterpropagating mode in the ring cavity.

The experimental apparatus is shown schematically in Fig. 1. The fundamental light is provided by a single-stripe, index-guided diode laser (Spectra-Physics SDL 5410-C), with maximum output power specified to be 100 mW at room temperature. The diode is housed in a small evacuated chamber that permits the laser to be cooled below 0°C so that we can access a wide range of wavelengths with temperature tuning. We also employ a closely mounted (≈50-μm) thin (≈150-μm) glass plate, which provides weak feedback into the laser and so slightly modifies the effective reflectivity of the outer laser-diode facet. Control of the position of this glass plate with a piezoelectric transducer allows us to select different longitudinal modes of the laser. This is important for spectroscopic purposes when a specific wavelength is desired. The spectroscopic experiments reported here were performed with the fundamental wavelength tuned to 840.6 nm. To this end the laser diode had to be cooled to −36°C.

The diode-laser output is focused into the four-mirror enhancement cavity, which is a bow-tie ring resonator with two curved mirrors and two planar mirrors.

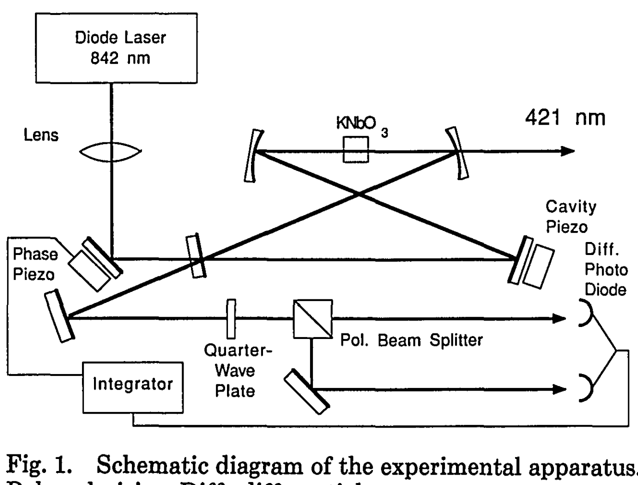

Fig. 1. Schematic diagram of the experimental apparatus. Pol., polarizing; Diff., differential.

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The planar input coupler has a reflectivity of 98%, while each of the three other mirrors has a reflectivity of 99.5%. The two curved mirrors, which are separated by $d_1 = 56$ mm, have radii of 50 mm. The optical path that connects the two curved mirrors through the two planar mirrors is $d_2 = 500$ mm. This specific design provides a small beam waist between the two curved mirrors that is adjustable by changing d_1. The maximum waist size that can be chosen is determined by the distance d_2. A second large waist at the center of the path d_2 allows for efficient mode matching. The diode-laser output is focused into this large waist of the ring cavity. The 5-mm-long $KNbO_3$ crystal is placed in the small focus of the cavity and oriented for second-harmonic generation by using the d_{32} coefficient. We achieve 90° phase matching by temperature tuning of the crystal. The confocal parameter b in the short arm of the cavity was calculated to be 2.1 mm outside the crystal, which yields $b = 4.8$ mm and a waist $w_0 = 0.017$ mm inside the crystal, since it has a refractive index of 2.28. Both crystal surfaces are antireflection coated for 850 nm. The enhancement of the fundamental beam is typically 19, which is limited mainly by poor mode matching (≈60%) of the astigmatic diode-laser beam to the TEM_{00} mode of the cavity. The enhancement is 30 without the crystal. The cavity is mounted inside an evacuated chamber on a solid aluminum block that is acoustically isolated from the bottom of the chamber by a layer of Viton. This combines resonator stability with the possibility of cooling the crystal below 0°C (the phase-match temperature for a 840.6-nm fundamental wavelength is −28.3°C).

The stabilization of the diode-laser frequency to the cavity resonance frequency is achieved by optical feedback from the counterpropagating fundamental mode that is excited in the ring resonator. The power in this counterpropagating mode can be large even for small values of the coupling between the two modes. To estimate this power, consider a ring cavity with an internal element, such as a weak reflector, that couples light from the forward-running mode to the counterpropagating mode. Assume that R is the fraction of power coupled from one mode into the other and that T is the fraction of power transmitted through the internal mode coupler. We define a quantity representing the losses of the coupling element by $A = 1 - R - T$. Furthermore, let R_1 denote the power reflectivity of the input coupler and R_m denote the cavity reflectance parameter representing all power losses in the resonator other than the input coupler and the internal mode coupler. If we define a critical coupling parameter

$$R_0 \equiv \frac{[1 - R_1R_m(1 - A)]^2}{[1 + R_1R_m(1 - A)]^2}(1 - A),$$

then for coupling values $R \leq R_0$ (weak coupling) the forward and reverse modes are resonant at the same frequency. The ratio of power in the two modes at resonance in this case can be written as

$$\frac{P_c}{P_f} = \frac{R}{[1 - (R_1R_mT)^{1/2}]^2},$$

where P_c (P_f) is the power in the counterpropagating (forward-running) mode. As R approaches R_0 the power ratio P_c/P_f approaches the value $1 - A$. If R exceeds R_0 (strong coupling), a splitting of the resonance frequencies occurs. In this regime at the resonance of the counterpropagating mode the power ratio P_c/P_f always takes the value $1 - A$. Note that R_0 can be rather small for typical values of R_1R_m (e.g., $A = 0$ and $R_1R_m = 0.96$ yields $R_0 = 1.6 \times 10^{-3}$).

In our resonator the reverse-mode coupling is provided by scattering from imperfections in the crystal faces. The crystal is slightly tilted such that the direct reflection is not matched into the reverse mode. Lateral translation of the crystal is sufficient in our experiment to adjust the feedback level to provide stable locking. To achieve optical locking only a small amount of feedback is necessary, approximately 10^{-4} of the diode power.[1] That this scattering provides the appropriate level of feedback can be roughly seen by the following argument. Assume that 0.1% of the forward power is uniformly scattered into a 2π solid angle from the input crystal surface. The cavity has a confocal parameter of 2.1 mm outside the crystal, corresponding to an opening angle of the beam of 0.032 rad. Thus only a fraction of approximately 1.3×10^{-4} of the scattered power is matched into the counterpropagating mode, resulting in $R = 1.3 \times 10^{-7}$. We assume that $T = 0.995$ owing to the antireflection coating of the crystal. These values together with $R_1 = 0.98$ and $R_m = 0.98$ yield $P_c/P_f = 2.5 \times 10^{-4}$, which is just of the right order of magnitude for optical locking. Moreover, R_0 has a value of 1.6×10^{-3}, showing that we operate in the regime of weak coupling ($R < R_0$). Therefore the forward-running and the counterpropagating modes are resonant at the same frequency. This is an important condition for our experiment since the resonance of the counterpropagating mode determines the optically locked laser frequency, while the forward mode must be in resonance to achieve high nonlinear conversion.

Optical locking is sensitive to the phase of the light returning to the diode and so depends on the optical path length from diode to cavity as well as the length of the cavity. To provide for more stable locking and also to be able to scan the laser frequency, we allow for control of the length between the diode and the resonator with a piezo-mounted mirror as shown in Fig. 1. We adjust this length so that the laser frequency optically locks to the peak of the cavity resonance. We employ a polarization-locking scheme[4] to servo control this length to the desired value. With this regulated phase control we are able to scan the laser frequency over 4 GHz by synchronously scanning the cavity length and the laser-diode current. In Fig. 2 the performance of the optical locking scheme is demonstrated. The feedback level is adjusted by lateral translation of the crystal to yield a locking range of approximately a third of a free spectral range (540 MHz) of the cavity (i.e., 180 MHz).

The maximum second-harmonic power that we have obtained is 6.7 mW, with 62 mW of laser input power and 1160 mW of circulating intracavity power. Thus the conversion efficiency is 0.57%, which results in a loss of fundamental power that is comparable with

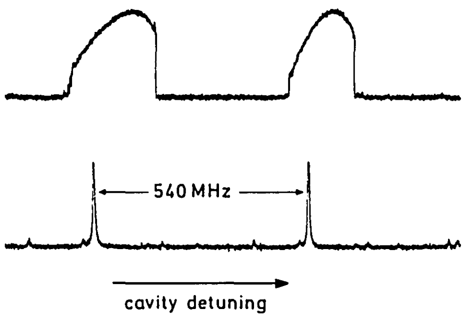

Fig. 2. Power transmitted through the cavity plotted versus the cavity detuning. The upper trace shows the case when optical feedback from the counterpropagating mode is present. In the lower trace the feedback is provided from elsewhere and the cavity is isolated from the laser diode.

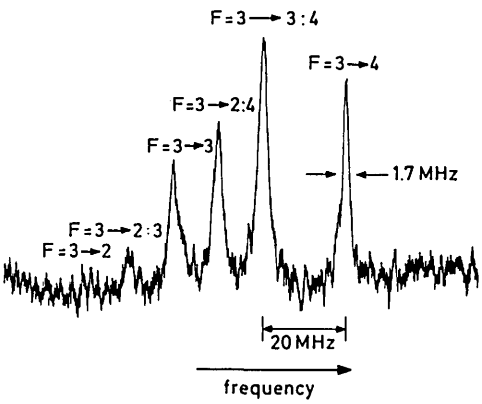

Fig. 3. Saturation spectrum of the $5S_{1/2}$:F = 3–$6P_{3/2}$:F= 2, 3, 4 transition in ^{85}Rb. Three hyperfine lines and the corresponding crossover lines are shown. The observed linewidth is 1.7 MHz; the scan rate was 6 MHz/msec. Sufficient laser power was available that no lock-in detection had to be employed.

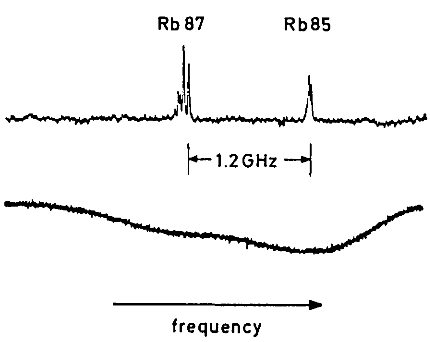

Fig. 4. A 4-GHz scan across the $5S_{1/2}$:F = 2–$6P_{3/2}$:F = 1, 2, 3 transition of ^{87}Rb and the $5S_{1/2}$:F = 3–$6P_{3/2}$:F = 2, 3, 4 transition of ^{85}Rb. The upper trace gives a Doppler-free saturation signal, while the lower trace synchronously monitors the corresponding Doppler-broadened absorption signal.

other intracavity losses. The unidirectional blue output is a TEM_{00} Gaussian beam since it is determined by the resonator mode rather than the laser-diode output beam. If we follow the method of Boyd and Kleinman,[5] the expected second-harmonic power for 1160 mW of fundamental power and a value[3] of 20 pm/V for the electro-optic coefficient d_{32} is 16.3 mW. In this calculation we have used our calculated confocal parameter of 4.8 mm and assumed that the focus is located in the center of the crystal. The discrepancy between the expected power and the experimentally obtained power is not well understood but is comparable with the results of other authors.[2,3] Poor crystal quality may be partly responsible. In addition, the value of the d_{32} coefficient may not be so high as the value that we have assumed.[3]

We have used this 421-nm light to observe the $5S_{1/2}$–$6P_{3/2}$ transition in rubidium. This line has a natural linewidth of 1.42 MHz and so provides an interesting test for our stabilized, tunable violet light. In addition, this transition (or the nearby $5S_{1/2}$–$6P_{1/2}$ transition) may prove to be a valuable tool in laser-cooling studies of rubidium. The short wavelength of this transition means that it could be used for Bragg scattering from arrays of channeled atoms.[6] Figure 3 presents a Doppler-free spectrum of the $5S_{1/2}$:F = 3–$6P_{3/2}$:F = 2, 3, 4 transition of ^{85}Rb obtained with standard saturation spectroscopy in a heated rubidium cell. The observed linewidths of 1.7 MHz are limited by inhomogeneous magnetic fields partly created by magnetic bases in our apparatus. In Fig. 4 a combined spectrum is shown of the transition given above and the $5S_{1/2}$:F = 2–$6P_{3/2}$:F = 1, 2, 3 transition of ^{87}Rb demonstrating a 4-GHz scan. The scanning performance of the laser system is restricted only by the piezoelectric elements employed. From spectra as in Fig. 3 taken at various scan rates we deduce that our laser linewidth does not exceed 1 MHz for observation times between 1 and 100 msec. However, we believe that an analysis with higher resolution will reveal the linewidth to be of the 10-kHz level, which is typical for optically stabilized diode lasers.[1]

In summary, we have generated the second harmonic of the 842-nm output of a GaAlAs diode laser in a $KNbO_3$ crystal in a resonant, external ring cavity. The diode laser is optically stabilized to the ring cavity by means of feedback from the counterpropagating fundamental wave, which is weakly excited in the resonator. We have produced 6.7 mW of tunable, narrowband radiation at 421 nm and have used that light to perform saturation spectroscopy on narrow transitions in rubidium.

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