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Maiman revisited: tuneable single mode CW ruby ring laser

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Abstract

The cw ruby laser reveals amazing properties, which have not been expected since its invention 60 years ago. CW pumping with a 405 nm laser diode requires an overall electrical power of only 6 W to achieve more than 100 mW in TEM_{00} at 694 nm for a linear resonator. In a ring cavity unidirectional single frequency operation with up to 75 mW, tuneable over more than 420 GHz is demonstrated. Experimental details will be presented, and possible applications will be discussed.

1. Introduction

60 years back, on May 16th, 1960, T. Maiman realized the first laser ever, the ruby laser [1]. The ruby laser is a three-level laser which needs population inversion with respect to a fully populated ground state. Despite strong warnings from highly reputed scientists, Maiman followed his idea [2]. In fact, considering other proposed and investigated laser materials at the end of the nineteen fifties [3], pink ruby [4] surely was the best suited at this time, due to the long fluorescence lifetime of the upper laser level of about 3.5ms, which allowed storage of pump energy and due to the very broad absorption bands [5], which allowed the use of broadly emitting xenon flashlamps for optical pumping. In the following, flashlamp pumped pulsed ruby lasers found many applications for material processing, holography, eye surgery, skin treatment, just to name a few.

The question whether cw operation of ruby is possible was successfully answered already in 1962, by demonstration of arc lamp pumping [6] and in 1970 by pumping with argon ion lasers [7], by cooling the crystal to liquid nitrogen temperature to lower the fluorescence linewidth [8]. However, these cw schemes were difficult and costly and never found any practical use. Also, the cw ruby laser pumped with a frequency doubled diode pumped cw Nd:YAG laser, realized in 2009 by the Klastech company [9], was not a real progress and practical scheme. Analyzing the needs for a real practical system, only direct cw diode laser pumping at wavelengths close to the optimum of the ruby absorption bands (555 nm and 405 nm) [5] seems to be adequate. Around 555 nm no suitable diode lasers exist, but fortunately very powerful and reliable diode lasers are available at 405 nm for a couple of years. In 2019, we first demonstrated cw laser oscillation of ruby in linear and ring resonators, pumped with such laser diodes [10]. In these first experiments, thresholds around 200mW and output powers up to 35 mW (at 1000mW pump power) were achieved. Calculations thereby indicate that for low loss optical resonators and using laser diodes with optimized, almost Gaussian beams profiles, even much lower thresholds should be possible. In fact, using a simple plano-concave optical resonator and pumping with transverse single mode GaN diodes with additional beam shaping optics, thresholds as low as 60 mW and output powers of 44 mW at 320 mW pump power have been reported recently [11].

These unexpected low thresholds, high efficiencies and high output powers create new interest for the development of a small size powerful laser source, which provides a high coherence length for space and industrial metrology. Thus, the potential of diode pumped cw ruby lasers needs further exploration. Besides output power and efficiency, the spectral characteristics, as mode spectrum, tuneability and the linewidth of single frequency systems are of interest.

The ruby crystal used in this work can be traced back to the original material from the early nineteen sixties. In the scope of a cooperation, it was handed by Theodore Maiman himself to Herbert Welling, the German laser
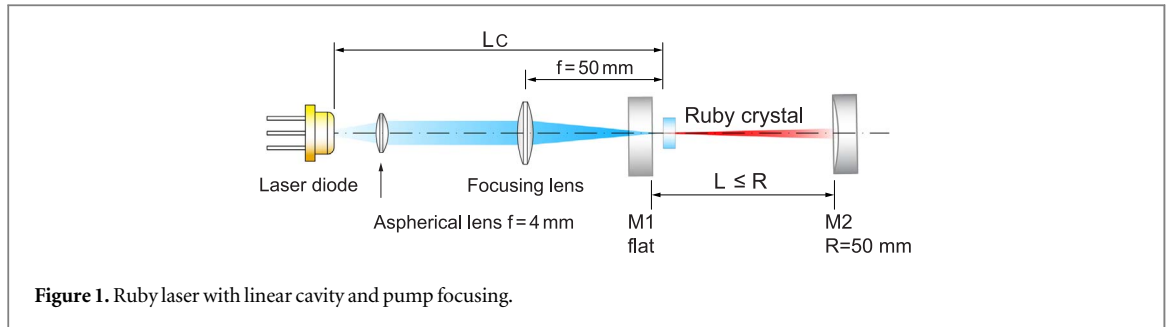
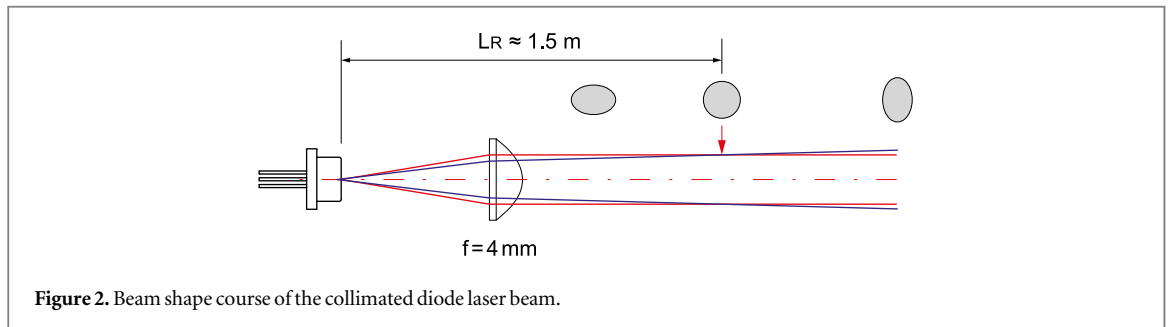**Figure 1.** Ruby laser with linear cavity and pump focusing.

Figure 2. Beam shape course of the collimated diode laser beam.

pioneer from Hannover. It was used for a few experiments back then and remained more than 50 years in the basement of the institute. Now with the availability of highly brilliant laser diodes it has been reactivated, and we will report on investigations on the mode spectrum in linear and ring resonators. Using an internal Faraday rotator with a TGG crystal, unidirectional single frequency ring laser oscillation with output powers up to 75 mW is achieved. With an additional birefringent tuner, single frequency emission with tuning of more than 420 GHz could be demonstrated. Features of different ruby laser designs and potential applications will be discussed.

2. Experimental

2.1. Linear cavity

The figure 1 shows the setup for the ruby laser with a linear cavity consisting of the flat mirror M1 and a curved mirror M2 with radius of curvature of 50 mm. The mirror M1 has a high transmission for the pump wavelength of 405 nm and a high reflectivity of >99.9% at 694 nm. The mirror M2 has a high reflectivity for the pump radiation and a transmission of 1% at the ruby laser wavelength of 694 nm. The ruby crystal (Cr_2O_3 concentration about 0.05%, *c*-axis 60° to crystal axis, AR coating 0.2% at 694 nm and 3% at 405 nm on both flat sides) has a thickness of 5 mm and a diameter of 9.5 mm and is mounted with an Indium foil into a passive cooler. The laser diode emits a wavelength of 405 nm with a maximum power of 1.3 W with a typical elliptical beam shape with a 1:3 ratio. The beam is collimated by a parabolic lens with a focal length of 4 mm. The position of the collimator is chosen in such a way that there is a crossing of the fast and slow beam. At the crossing point, the beam is circular (fig. 2).

The position L_R depends on the astigmatic difference of the used laser diode. In our experiment we used a model which provides a circular spot at a distance L_R of ∼1.5 m, however, along with the focusing lens, the round spot is shifted to a distance L_c (fig. 1). If the ruby crystal is positioned at this location L_c, the best pumping efficiency and highest output power in TEM_{00} is achieved (see fig. 3).

The figure 3 shows the output power of the ruby laser versus the pump power, with an almost linear increase above a pump power of about 300 mW. At lower pump power, changes of the beam geometry of the pump diode leads to a slight non-linear behavior.

The ruby crystal is located close to the mirror M1 and the laser diode along with its collimator in the distance $L_c = 360$ mm. A deviation of ±5 mm of this distance leads to a drop of the output power of 50%, and a rich variety of unwanted transverse modes occur. At present, the mirror M2 has a transmission of 1% at 694 nm yielding a threshold of 130 mW and a maximum output power of 110 mW in TEM_{00} at a pump power of 1.25 W. In our previous publication [10] we reported 36 mW at a pump power of 1.2 W and a transmission of 1.8%. It is expected that the ruby laser output power can be increased further when using a higher output coupling. Considering the overall electrical power input for the laser diode of 6.6 W to achieve 1.2 W of pump power and
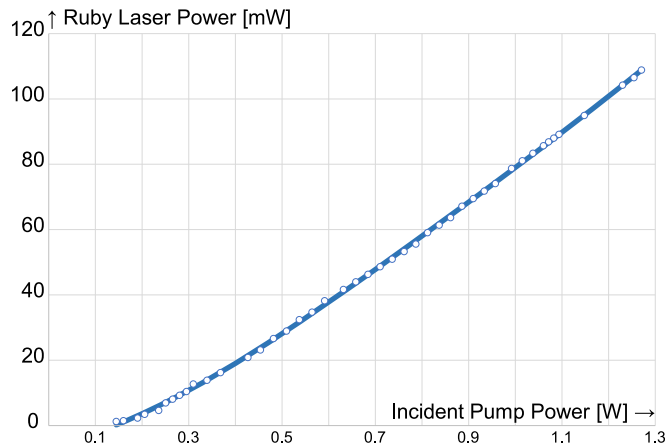
Figure 3. TEM_{00} output power of the ruby laser with a linear cavity and optimum pump focus at distance L_C (360 mm).
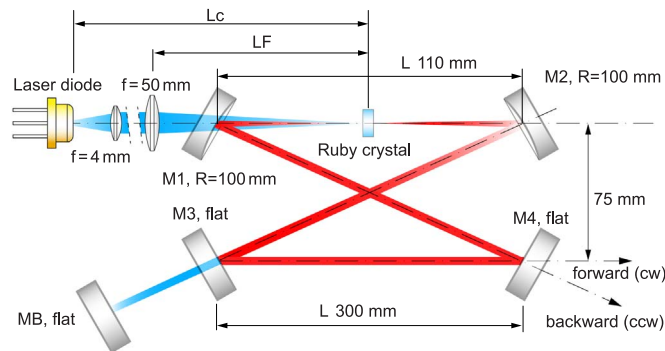

Figure 4. Bow tie cavity with additional back pump mirror MB.

already more than 100 mW of ruby laser output, the diode pumped ruby laser belongs to the most powerful and efficient lasers in the visible spectrum having a TEM_{00} emission.
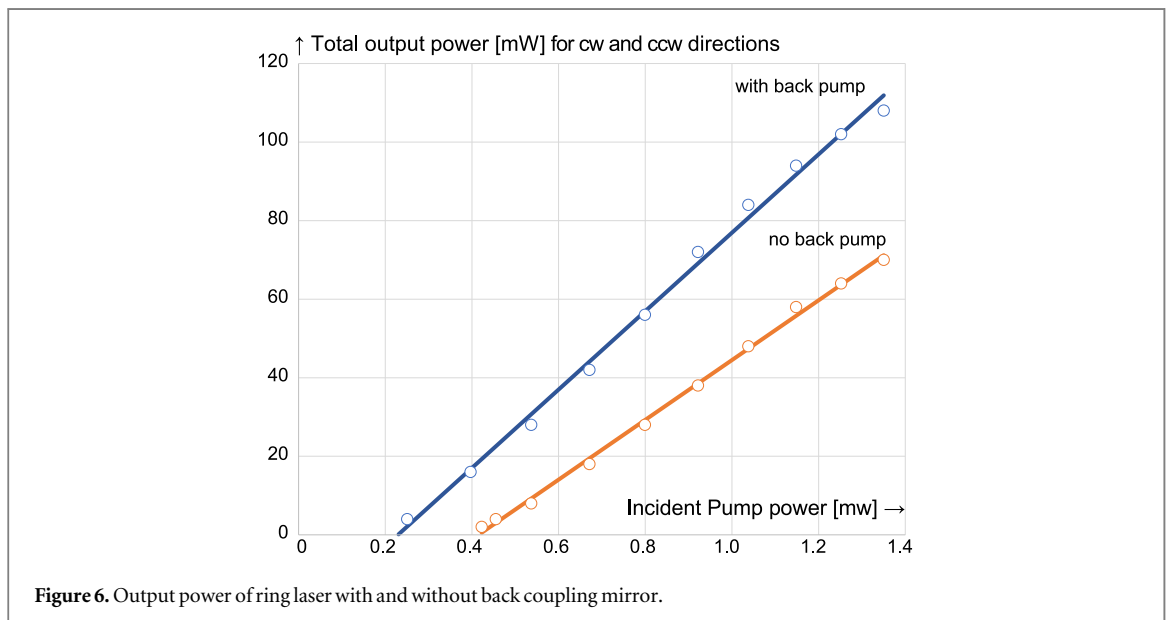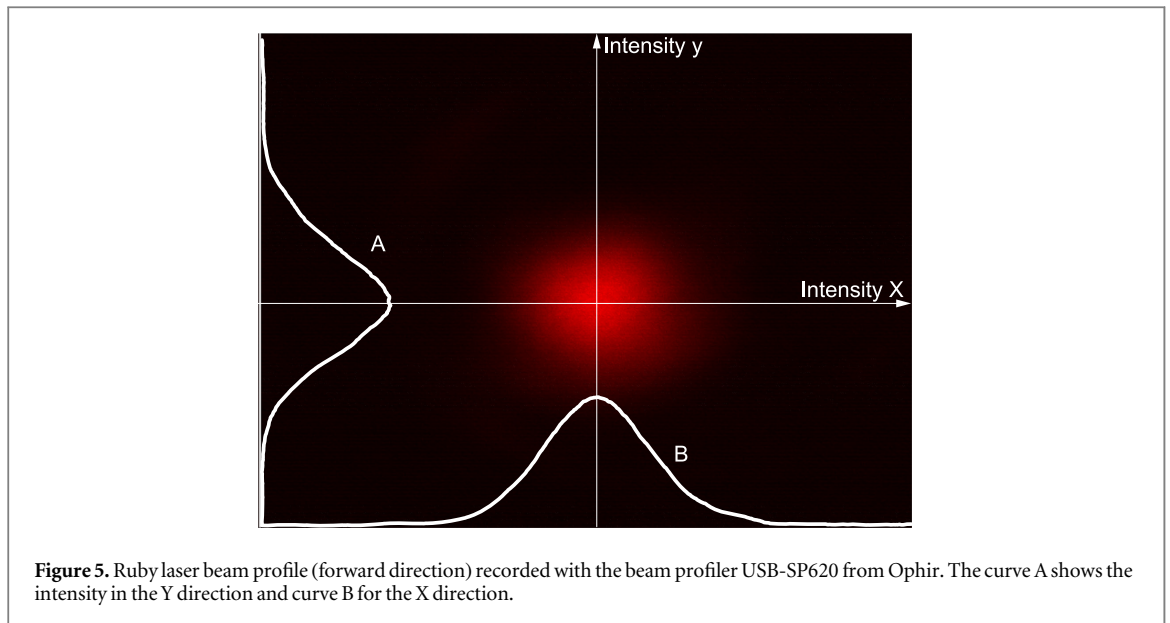
2.2. Ring cavity

For single mode operation of the ruby laser and investigations of linewidth and stability, a ring resonator is suited best. As in our previous publication [10] we used a bow tie resonator as shown in fig. 4.

The ruby crystal is now placed in the middle between the two curved mirrors M1 and M2 (radii 100 mm). The pump radiation is focused with an f = 50 mm lens at a distance of L_F through the mirror M1 (high transmission at 405 nm, high reflection at 694 nm) into the ruby crystal in such a way, as described above, that the round focus spot lies right in the middle of the ruby crystal at distance L_C. The optimum position L_F of the focusing lens is visually inspected (see fig. 5 in [10]). The mirror M4 is flat and has a high reflectivity for the pump radiation and 1% transmission at 694 nm. M3 is also a flat mirror, but with a high transmission for the pump radiation and high reflectivity for 694 nm. An additional back coupling mirror MB (flat, high reflectivity for 405 nm) outside the cavity is used to feed back non-absorbed pump radiation into the ruby crystal.

With this setup, simultaneous TEM_{00} oscillation in forward (cw, with respect to pump direction) and backward (ccw) direction is obtained (see fig. 5). Figure 6 gives the output power (added for both directions) versus pump power curves for with and without the back coupling mirror, showing the dramatic influence of the back coupling mirror both on threshold and output power. With no back coupling, the total output power is 70 mW and increases to 115 mW (at 1.4 W pump power) with the back coupling mirror. In our previous publication (fig. 07 [10]) it has been shown that the pump absorption strongly depends on the pump power. At a pump power of 1.2 W, only 60% are absorbed. We assume that back coupling increases the pump volume and with it the output power.

A specific operation mode of a laser with a ring resonator is unidirectional travelling wave oscillation. This is achieved here by placing a Faraday rotator and a half-wave plate (HWP) inside the ring cavity of fig. 4 between that flat mirrors M3 and M4. The Faraday rotator consists of a TGG crystal (Terbium gallium garnet, with AR

Figure 5. Ruby laser beam profile (forward direction) recorded with the beam profiler USB-SP620 from Ophir. The curve A shows the intensity in the Y direction and curve B for the X direction.

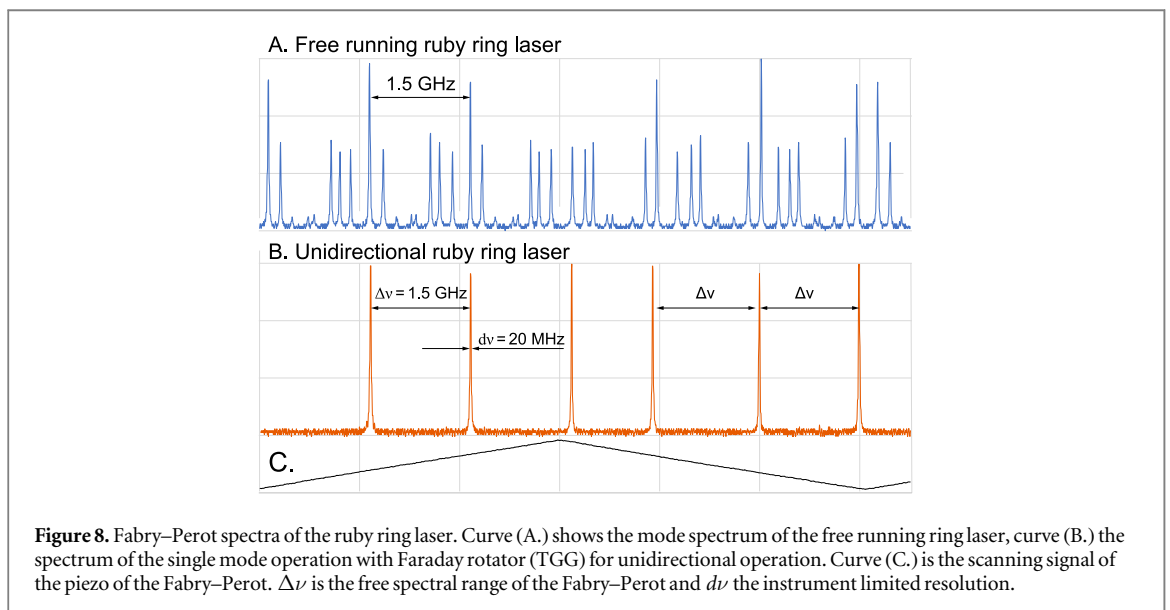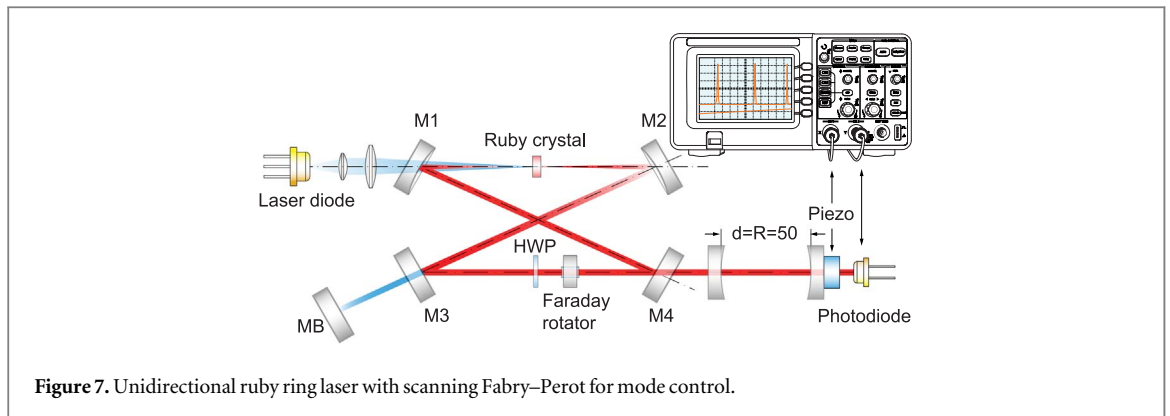**Figure 6.** Output power of ring laser with and without back coupling mirror.

coatings at 694 nm on both sides) with a diameter of 6 mm and a length of 8 mm placed into a strong permanent magnet with longitudinally oriented magnetic field. Depending on the adjustment of the TGG (tilting and turning around the optical axis) and the half-wave plate, operation in the cw (forward) and ccw (backward) mode or oscillation in both directions is possible. It should be noted that unidirectional oscillation even can be obtained without the half-wave plate as the ruby crystal exhibits a weak birefringence and itself acts as an active polarization element and cancels out the Faraday rotation in one direction, however, at the expense of direction stability.

The threshold in cw or ccw mode is about 320 mW and so far, a maximum output power of 75 mW at 1.2 W pump power (1% output coupling) has been achieved at unidirectional travelling wave operation. As will be shown and discussed below, in cw or ccw mode, the laser mostly oscillates in a single frequency.

2.3. Mode spectrum and single frequency operation

For potential applications of the ruby ring laser in metrology, the longitudinal mode (frequency) spectrum is important. It is measured here with a scanning Fabry–Perot interferometer (SFP) added to the experimental setup as shown in fig. 7, consisting of two spherical mirrors with radii R of 50 mm (transmission 1% at 694 nm) at distance $d = R$ (confocal configuration). One mirror is attached to a PZT actuator which is periodically elongated with 35 Hz at a maximum amplitude of 10 μm. The free spectral range of the SFP for the confocal configuration is given by $\Delta\nu = c/4d = 1.5$ GHz.

Figure 7. Unidirectional ruby ring laser with scanning Fabry–Perot for mode control.

Figure 8. Fabry–Perot spectra of the ruby ring laser. Curve (A.) shows the mode spectrum of the free running ring laser, curve (B.) the spectrum of the single mode operation with Faraday rotator (TGG) for unidirectional operation. Curve (C.) is the scanning signal of the piezo of the Fabry–Perot. $\Delta\nu$ is the free spectral range of the Fabry–Perot and $d\nu$ the instrument limited resolution.

The figure 8 shows the frequency response of the Fabry–Perot for the free running ring laser without Faraday rotator (curve A.) and (B.) for the unidirectional ruby ring laser. The curve (C.) shows the piezo voltage. Both curves have been taken sequentially without changing the parameters, except that for curve (B.) the Faraday rotator has been set into the cavity. The curve (B.) clearly shows single frequency operation, which is expected due to the homogeneous line broadening as discussed below, while the free running ring laser shows a more or less chaotic fluctuating mode structure, as it is common for homogeneously broadened gain media due to strong mode coupling inside the active media. Mode coupling effects in He–Ne ring lasers have been treated theoretically and experimentally [12]. One source of coupling is back scattering, which is much stronger in the ruby laser than in the He–Ne case because mode mixing not only comes from the cavity mirrors, but also from the ruby gain medium itself. Another source of coupling is the population inversion grating established in the ruby crystal due to gain saturation [13]. As soon as the ruby ring is set to unidirectional operation, the desired clean and stable single mode operation is obtained. The mode spectrum measured with the Fabry–Perot (fig. 8 curve B.) indicates a linewidth of less than 20 MHz, given by the resolution $d\nu$ of the Fabry–Perot. It is expected that the real single frequency linewidth will be lower by at least an order of magnitude. Measurement of this linewidth by beat frequency experiments with two identical, but independent ruby ring lasers are in preparation and will be presented in a forthcoming paper.

For cw ruby lasers operated in linear resonators, the fluctuating mode structure is very similar as for the ring. With an internal etalon, the number of modes can be reduced to two or even one mode. However, this operation is very unstable with more or less strong frequency and intensity fluctuations. The same is observed in the bidirectional operation modus of the ring (without Faraday rotator TGG) when inserting an etalon. This behavior presently seems to prevent the use of a ruby ring laser as a laser gyro. Whether specific stabilization schemes, such as recently applied for a diode pumped Nd:YAG ring laser gyro [13], or other techniques may overcome this problem, remains open.
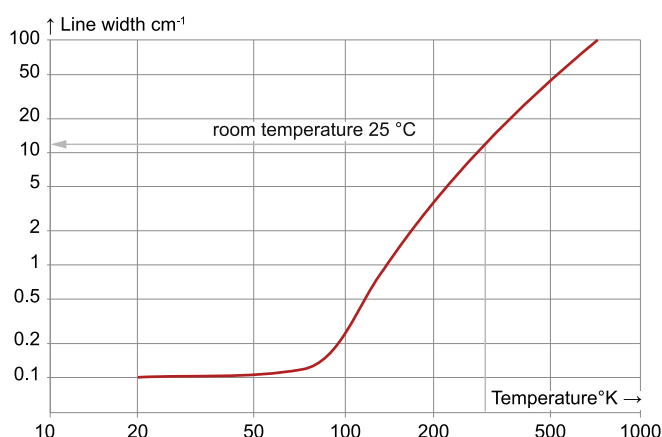
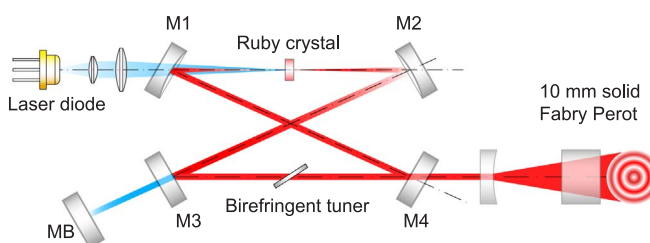**Figure 9.** Ruby fluorescence linewidth versus temperature after [8].

Figure 10. Setup for tuning the ruby ring laser.

2.4. Wavelength tuning

The fluorescence lifetime of ruby is 3.5 ms, which in principle would lead to an extremely narrow linewidth of about 45 Hz. However, due to Raman scattering and crystal inhomogeneities the fluorescence emission is homogeneously broadened ([8, 14]) and strongly depends on the temperature as shown in fig. 9.

Therefore, for a ruby crystal at room temperature, we expect a fluorescence linewidth of 11 cm^{-1} corresponding to 330 GHz or 0.5 nm. Consequently, the ruby laser should allow tuning over a more or less big part of this emission width. A simple setup to check the tuneability is shown in fig. 10.

The ring laser is now operated with an internal birefringent tuner (quartz, thickness 0.9 mm, under Brewster angle) instead of the Faraday rotator (TGG). The tuner allows oscillations on a number of coupling modes (similar as shown in fig. 8 (A.)) in a certain spectral range, defined by the tuner. The output of the ruby laser is slightly expanded by a lens and divergently sent through a solid quartz Fabry–Perot (thickness 10 mm, coatings with reflectivity of about 20 %) resulting in Fabry–Perot rings as indicated in fig. 10. The frequency spacing of the rings (free spectral range) is given by the optical thickness of 14.6 mm (refractive index of quartz about 1.46), corresponding to about 10 GHz. As the spectral distance of the ring laser modes is about 350 MHz (length of ring resonator 85 cm) they will not be resolved by the Fabry–Perot. But by slightly turning the birefringent tuner, the spectral emission of the ring laser is shifted and the ring structure of the Fabry–Perot swells accordingly. The moving rings can be counted easily. So far, we counted 42 orders, corresponding to a tuning range of about 420 GHz, presently limited by the tuning range of the birefringent tuner (optimized thickness). To achieve wide and true continuous single frequency tuning of the unidirectional ruby ring laser (with Faraday rotator TGG), the optical resonator length has to be controlled and accordingly shifted by suitable elements like PZT, pressure cell or others. The so far measured emission bandwidth of 420 GHz is more than predicted by fig. 9 at room temperature and indicates that the temperature within the tiny ruby crystal pump channel is much higher.

3. Conclusions and outlook

60 years after its first realization, the ruby laser shows an interesting comeback as an efficient all solid state 405 nm diode laser pumped cw laser system for the red spectral range. For a semi-concentric resonator diode laser, pump thresholds as low as 100 mW and output powers of more than 100 mW at 1.3 W pump power have been realized so far. With a ring resonator setup, unidirectional single frequency emission with output powers

up to 70 mW have been achieved. The homogeneously broadened emission line allows tuning of more than 400 GHz. Simple Fabry–Perot linewidth measurements indicate at present an instrument limited linewidth below 20 MHz. It is expected that planned beat experiments with two independently operated ring lasers will yield linewidth in the kHz range, which will open up new applications in long range metrology. Further on, by frequency doubling within the ring laser, a highly coherent tunable source around 347 nm will be possible. Indeed, in some first experiments 5 mW at 347 nm could already be demonstrated, and detailed results will be presented in a forthcoming paper.

Thus, the fascinating story of the ruby laser will continue.

Acknowledgments

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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