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Spectrochimica Acta Part B 53 (1998) 763–768

SPECTROCHIMICA
ACTA
PART B

Technical note

Second harmonic generation applying injection-locked radiation from a high-power, broad-stripe laser diode

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Received 26 January 1998; accepted 18 March 1998

Abstract

406 nm laser light is produced by second harmonic generation in a $LiIO_3$ crystal using the fundamental radiation of an injection-locked, broad-stripe, high-power laser diode. The efficiencies of injection locking as well as of second harmonic generation are discussed.

Keywords: Laser diode; Injection locking; Second harmonic generation

1. Introduction

Semiconductor laser diodes of the AlGaAs and InGaAsP type combine the special spectroscopic properties of tunable cw lasers, such as narrow band width and high spectral radiation density, with technical properties which are necessary when designing compact spectrochemical instruments with high detection sensitivity for routine operation. Such technical properties are, for example, rapid wavelength tunability by diode current, low amplitude noise, high stability, long lifetime and small size. It has been shown that low detection limits can easily be obtained by diode laser atomic absorption spectrometry (DLAAS) because different sources of noise can be suppressed by simple experimental arrangements. General aspects of diode laser spectrometry, in particular, for element analysis, are discussed in a recent review [1].

The fact that laser diodes with wavelengths below 630 nm are still not commercially available is certainly a drawback for atomic spectrometry, where the resonance lines are mainly in the UV and blue spectral range. Nevertheless, it is possible to obtain tunable laser light below 630 nm by non-linear optical techniques, such as second harmonic generation (SHG) of diode laser radiation [2] or sum frequency generation (SFG). The SFG-technique is capable of generating wavelengths as low as 280 nm [3]. However, the power of the SHG or SFG radiation amounts to only 20–80 nW if the input powers are of the order of 40–50 mW. The low output of the non-linear techniques limits the detection power in DLAAS. For example, the shot noise limits absorption measurements to about 10^{-3} if 20 nW are used. On the other

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PII S0584-8547(98)00118-9

hand, about 2×10^{-7} absorption can be measured if 2 mW of laser power is applied, while still maintaining linear interaction between the radiation and the absorbing atoms [4]. The need for sufficient radiation power was recently demonstrated when we made isotope-selective measurements of Pb by DLAAS in a FANES cell using the $6p^2\ ^3P_2$–$6p7s\ ^3P_1^o$ transition at 406 nm [5]. The detection limit of Pb was not only poor because we probed a metastable initial level lying 1.32 eV above the ground state, but also because of the low radiation power generated by SHG.

There are two main approaches to achieve higher powers, i.e. lower detection limits in DLAAS. The first is the application of intra-cavity SHG or SFG, and the second the enhancement of the fundamental laser power by optical amplification before SHG or SFG. At a first glance, the latter approach seems to be the simpler and less expensive way for the generation of higher power since there are inexpensive multimode, broad-stripe laser diodes (price: about US$150) with high power (1 W) on the market which operate in the wavelength range around 810 nm. These laser diodes can be used as optical amplifiers for low-power single mode laser diodes working in the same spectral range (injection-locking technique). There are recent encouraging papers on successful amplification of single mode laser radiation in high-power, broad-stripe laser diodes [6–8]. We have therefore investigated the properties of optical amplification of low power single mode radiation in high-power laser diodes and the efficiency of SHG in a $LiIO_3$ crystal using the amplified radiation.

2. Experiment

The experimental arrangement used for amplification of laser radiation by injection locking is shown in Fig. 1. All components were mounted on a stable metal plate (size: $30 \times 35 \times 2\ cm^3$) in order to have a robust and compact device. A single longitudinal mode laser diode (LT016 by Sharp, power: 30 mW, wavelength at room temperature: 810 nm) was used as a master laser. It was operated by a commercial laser diode power supply (LDC 400 by Profile). The slave laser was a multi-mode, broad-stripe laser diode from Siemens (SFH 480402) with a maximum power of 1 W and a peak wavelength at room temperature of 809 nm. In contrast to the master laser diode, the Siemens laser diode comes without a hermetically sealed housing. This "open version" has the advantage that the optical access for the injection beam is better than for a diode with a window, but has the disadvantage that the laser chip is not protected against dust particles. The high power laser diode was driven by the high current version power supply from Profile (LDC 420B). The beam divergences of the Siemens laser diode were ±6° parallel and ±20° perpendicular to the active stripe. Both lasers were mounted with their junctions parallel to the surface of the metal plate, thus having the same beam polarization (x-direction). The master laser beam was collimated by a spherical lens (SL1) and aligned with two mirrors to the optical axis (y-direction) of the slave laser. Two different lenses (SL1) were used. One had a focal length of 4.0 mm and a numerical aperture of 0.45, and the other 3.1 mm and 0.65 respectively. To avoid feedback into the master laser and perturbations of the master laser due to the slave laser beam, a Faraday isolator was used. The 45° rotation of the polarization due to the Faraday isolator was rotated back by a half-wave plate placed behind the isolator to match the polarization of the slave laser. The master laser beam was focused into the junction area of the slave laser by a combination of cylindrical (CL) and spherical (SL2) lenses. The focal length of the cylindrical lens was 30 mm whereas the parameters of the spherical lens SL2 were identical to SL1. The focal beam shape was elliptical with the longer axis (x-direction) parallel to the junction plane (xy-plane). The

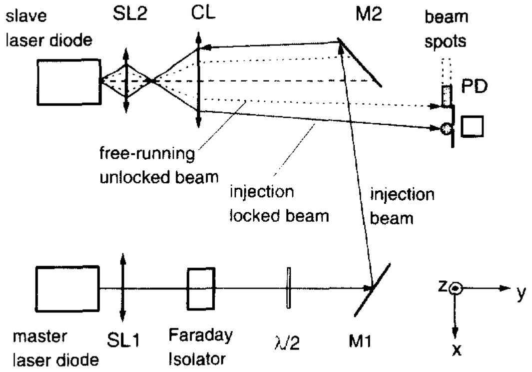

Fig. 1. Experimental arrangement. SL1 and SL2: spherical lenses, CL: cylindrical lens, M1 and M2: plane mirrors, PD: photodiode.

beam waists were about 15 μm and 1.5 μm in the x and y directions respectively.

SL1 was mounted on a precision xyz-stage, and the cylindrical lens CL was mounted on a precision xy-stage. The use of precision stages was necessary for stable and reproducible alignment of the incident angle of the injection beam with respect to the axis of the free-running slave laser. Various spatial modes could be selected by transverse motion (x-direction) of the spherical lens SL2 which changed the injection angle. The reflected amplified beam was measured by a photodiode fixed behind a diaphragm. The diaphragm could be shifted in the x-direction for the measurement of the mode structure of the slave diode.

It was found that the front facet of the slave diode could easily be damaged by air dust particles if they attached to the surface and were then burned by the high radiation intensity of the injection-locked laser. Therefore, the slave laser has to be protected against dust. We placed the laser as well as the combination of cylindrical and spherical lenses in a box which is not shown in Fig. 1.

The amplified radiation from the slave laser was focused by a spherical lens ($f = 10$ cm) into a 6 mm long $LiIO_3$ crystal for SHG. The lens and the crystal, both placed behind the diaphragm, as well as a calibrated power meter (Coherent Fieldmaster ML) for the measurement of the frequency-doubled radiation are also not shown in Fig. 1.

3. Results and discussion

In order to get stable and powerful single mode operation of the slave laser, the master laser beam has to be injected in the xy-plane into the slave laser diode. The injection angle is typically about 6°; the refraction and reflection angles inside the active region of the slave laser are about 2°. Fig. 2 shows the horizontal intensity distribution (x-direction) of the collimated slave laser beam with (full squares) and without (open circles) injection locking. The distance between the cylindrical lens and the diaphragm was 210 mm. The slave laser current was 620 mA, slightly above threshold (550 mA). While the slave laser beam was collimated in the zy-plane, it was slightly divergent in the yx-plane. Amplification was also observed in other spatial modes of the slave laser diode by increasing or decreasing the injection angle in the xz-plane. However, the amplified radiation powers in these modes were smaller than in the optimum case shown in Fig. 2.

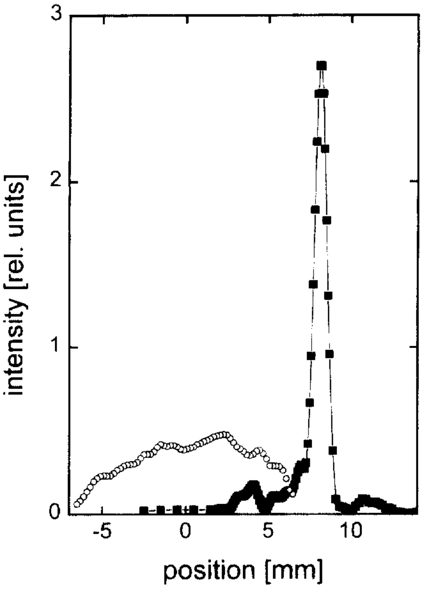

Fig. 2. Intensity of the free running (○) and injection locked (■) slave laser beam in the x-direction.

The mode matching can be described by considering the master laser beam injected into a Fabry–Perot cavity. Assuming a Fabry–Perot model [6] for the broad-stripe slave diode, the resonance condition of the cavity depends on the wavelength of the master laser, the electron density in the active region, the temperature of the slave laser diode, and the injection angle of the master laser beam. The dependence of the resonance condition for an injected beam with fixed laser wavelength on temperature and current of the slave laser is demonstrated in Fig. 3(a) and Fig. 3(b) respectively. The data displayed in Fig. 3(a) were obtained with a constant slave diode current of 860 mA. The temperature difference between two intensity maxima is 2°C. The intensity dependence shown in Fig. 3(b) was measured at constant temperature. The current difference between the maxima was about 220 mA. A very important consequence for diode laser spectroscopy with injection-locked broad-stripe laser diodes is that one has to find the optimum resonance conditions for the amplified

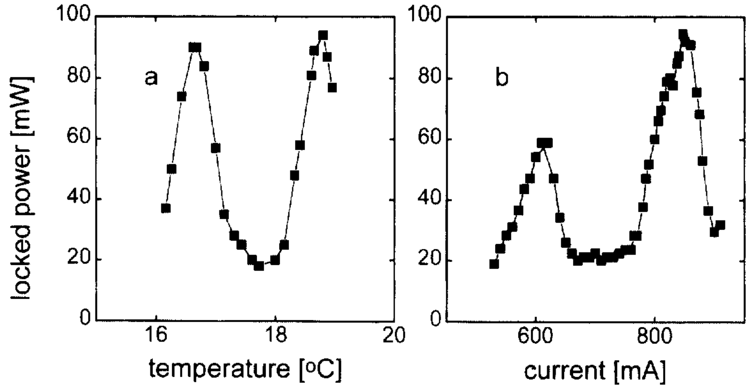

Fig. 3. Power of the injection-locked laser beam as a function of (a) temperature and (b) current of the slave diode.

mode by variation of temperature or current, so that the wavelength of the master laser can be tuned over a large wavelength range without significant reduction of the amplified laser power.

As mentioned above, we used two sets of collimator lenses with different numerical apertures. The intensity distribution in the x-direction was always Gaussian irrespective of the spherical lenses used. However, higher injection-locked powers were achieved with the smaller aperture lens. Intensity distributions of the injection-locked slave laser beam in the x-direction obtained with the small aperture lens at three different slave diode currents are shown in Fig. 4. The measurements were performed at constant slave diode temperature. The resonance conditions were fulfilled by matching of the master laser wavelength. It can be seen that the direction of the injection-locked laser beam is dependent on current. The spatial angle of the beam becomes larger with higher current since the index of refraction of the laser medium increases with the electron densities. On the other hand, the power of the locked as well as of the unlocked part of the beam increases with slave diode current. However, the increase of the unlocked beam power was stronger than that of the locked beam. This means that the injection-locking efficiency becomes smaller at higher slave laser currents. The injection-locking efficiency, defined as the ratio of the locked power to the total power of the slave laser, as a function of the slave laser current is given by the open circles in Fig. 5. The locking efficiency, which is about 80% slightly above threshold current, exhibits a linear decrease with current. The efficiency was only about 30% at the maximum slave diode current (1.6 A). On the other hand, the total power of a free-running slave laser increases linearly with diode current (full circles in Fig. 5). Combining the linear fits through the measured data of the free-running power and the locking efficiency, we obtain the optimized injection-locked power as a function of the slave laser current, shown as the lower dashed curve in Fig. 5. The experimental data for the locked power, except for one (■), are not shown in Fig. 5.

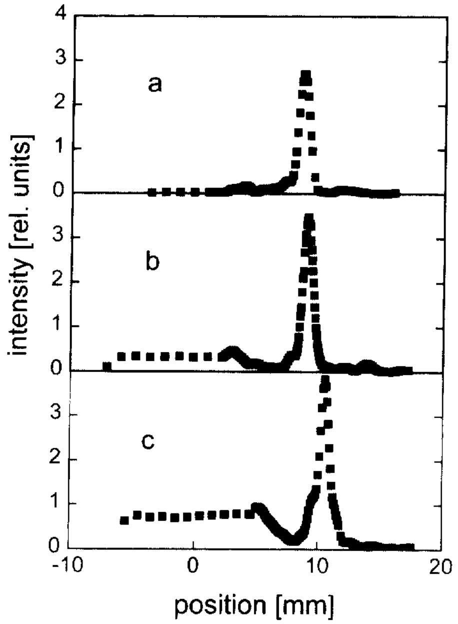

Fig. 4. Intensity in the x-direction as a function of the slave diode current: (a) 650 mA, (b) 850 mA, and (c) 1050 mA.

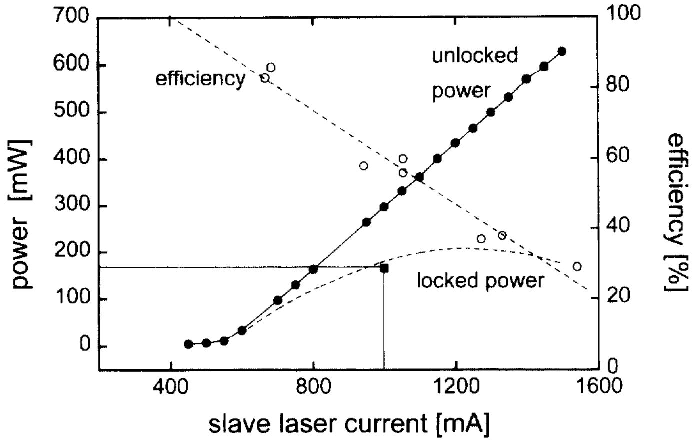

Fig. 5. Power of the free-running power slave laser, efficiency of injection locking and power of the locked slave laser as a function of the slave diode laser current (power of the master laser: 30 mW).

They scattered around the dashed curve. For currents of about 1.2 A, the injection-locked power curve reached its maximum (about 230 mW). The efficiency of injection locking in our experimental arrangement was comparable with the efficiencies found in the earlier papers on amplification of single mode laser diode radiation in high-power broad-stripe laser diodes [6–8].

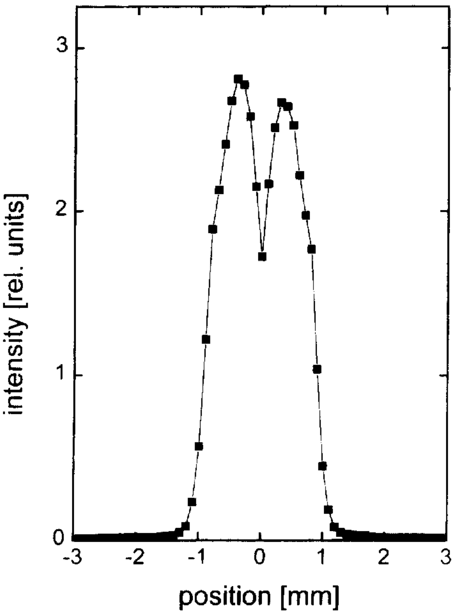

Fig. 6. Intensity distribution of the collimated injection-locked beam in the z-direction, as measured with the the 0.45 aperture lens.

The spatial profiles of the injection-locked beam obtained behind the 0.45-aperture lens were different in the x- and z-directions. Whereas the profile was Gaussian in the x-direction, it consisted of two overlapping profiles in the z-direction (see Fig. 6). Since the original slave laser beam is characterized by a large divergence in the zy-plane (~40°), the collimated beam is influenced by diffraction at the lens edges resulting in the far-field structure observed. The same diffraction can also be observed in the z-direction if the slave laser runs without injection locking. This means that the divergence of the slave laser in the z-direction is too large for the lens chosen. The diffraction structure in the z-direction can be avoided and a pure Gaussian injection-locked beam can be produced if lenses with larger numerical aperture, e.g. 0.65, are used. However, this is at the expense of the injection-locked beam power. We found that the power is reduced by 50% if the 0.65 instead of the 0.45 aperture lens is used.

The mode structure of the amplified radiation was controlled by a 2 GHz free spectral range scanning Fabry–Perot interferometer (finesse: about 60). The injection-locked beam had good single mode structure up to about 1 A slave laser current. Beyond 1 A, unlocked modes became visible.

The SHG efficiency was measured by applying both sets of lenses and using a spherical lens (focal length: 10 cm) for focusing the amplified radiation into the $LiIO_3$ crystal. The slave laser current was set to 1 A. The power of the locked beam was

170 mW using the 0.45 aperture collimator lens (see full square in Fig. 5). About 100 nW SHG power was generated in this case. On the other hand, more SHG power (150 nW) was obtained with the large aperture collimator lens at the same slave laser diode current, despite the fact that the power of the amplified radiation was only 80 mW. Indeed, 150 nW blue light is expected for 80 mW fundamental power of a Gaussian beam if we take into account the quadratic dependence of the SHG process and the 20 nW blue light obtained with a 30 mW laser diode in our earlier experiment on Pb [5]. The poor SHG-efficiency obtained with the injection-locked beam in the first case was certainly due to diffraction losses and to the large divergence of the non-Gaussian beam in the z-direction which could not completely fulfil the phase matching condition in the $LiIO_3$ crystal.

Taking into account our experimental results, we anticipate that it should be possible to produce about 140 mW of amplified radiation with a more appropriate divergence for efficient SHG if a lens with about 0.55 aperture is used. This means that one can expect approximately 450 nW at 406 nm using the 6 mm long $LiIO_3$ crystal. However, the SHG power is not high enough to justify the costs of the experimental arrangement presented. It is more straightforward to use directly a single mode laser diode with 150 mW power such as are commercially available for 810 nm, for example from Spectra Diode Labs (SDL). These laser diodes are expensive, but their price is comparable with the costs of a good Faraday rotator and $\lambda/2$-plate which are necessary for injection locking.

In conclusion, we do not see advantages in the application of injection locking of high power laser diodes for SHG of 406 nm radiation. However, we want to stress that injection locking is certainly a good approach if high SHG powers have to be produced in other wavelength ranges where high-power single mode laser diodes are not commercially available. There are, for example, still no high-power single mode laser diodes of the InGaAsP type which operate in the wavelength range 670–690 nm. However, 1 W broad-stripe InGaAsP laser diodes can be purchased, for example, from Philips.

Acknowledgements

The work was performed within the framework of a scientific and technological co-operation project funded by the Federal Ministry of Education, Science, Research and Technology of the Federal Republic of Germany and the Ministry of Science and Technology of the Republic of Croatia.

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