Wavelength-Stabilized Compact Diode Laser System on a Microoptical Bench With 1.5-W Optical Output Power at 671 nm

Martin Maiwald, Arnim Ginolas, André Müller, Alexander Sahm, Bernd Sumpf, Götz Erbert, and Günther Tränkle

***Abstract*—A wavelength-stabilized compact diode laser system emitting at 671 nm mounted on a microoptical bench with the dimensions of 13 mm × 4 mm is presented. A reflecting Bragg grating was aligned on the rear side of a broad-area gain medium for wavelength stabilization at 671 nm. A maximum output power of 1.5 W was obtained together with a spectral width of 40 pm (full-width at half-maximum). At 1.0 W, a center wavelength stability below 20 pm over 5 h was determined. With these features, the devices are well-suited for spectroscopic applications.**

***Index Terms*—Gratings, laser resonators, light sources, optical feedback, Raman spectroscopy, semiconductor lasers.**

I. Introduction

HIGH-POWER red emitting diode lasers are promising light sources in several applications like laser display technology, photodynamic therapy, and as pump sources for frequency conversion to the ultraviolet (UV) spectral range.

For Raman spectroscopy of most solid and liquid samples excitation light sources with a long-term center wavelength stability better than 1 cm^{-1} (i.e., ≈45 pm at 671 nm) and a spectral width below 10 cm^{-1} (i.e., ≈450 pm at 671 nm) are required. The high stability is necessary for a calibration free operation over large periods (see, e.g., [1]) and the emission width had to be smaller compared to the width of the characteristic Raman lines. Beside the spectral requirements, an output power larger than 100 mW is required to reach appropriate Raman signals within short integration times.

Diode lasers with a small spectral linewidth using internal gratings like distributed-Bragg-reflecting and distributed-feedback lasers have shown output powers of 25 mW at 670 nm and 90 mW at 662 nm, respectively [2]. System considerations concerning a wavelength-stabilized laser diode at 658 nm using a volume holographic grating were presented [3].

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The authors are with the Optoelectronics Department, Ferdinand-Braun-Institut für Höchstfrequenztechnik, 12489 Berlin, Germany (e-mail: Martin.Maiwald@FBH-Berlin.de; Arnim.Ginolas@FBH-Berlin.de; Andre.Mueller@FBH-Berlin.de; Alexander.Sahm@FBH-Berlin.de; Bernd.Sumpf@FBH-Berlin.de; Goetz.Erbert@FBH-Berlin.de; Guenther.Traenkle@FBH-Berlin.de).

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One reason for the limitation of the output power is the more challenging design of the vertical layer structure for red emitting devices in comparison to longer wavelength lasers. The implementation of a highly carbon-doped p-side AlGaAs cladding layer recently allowed the development of highly efficient 670-nm broad-area (BA) lasers [4]. An output power up to 5.5 W and a conversion efficiency larger than 41% was demonstrated.

In this letter, a comparable laser structure is used as BA gain media in a wavelength-stabilized compact high-power diode laser system emitting at 671 nm (e.g., suitable for *in situ* Raman spectroscopy). The microsystem laser devices will be described. The properties of their components (i.e., the BA gain medium, the microoptics for beam shaping, and the reflecting Bragg grating (RBG) for wavelength stabilization) will be given. The power–current characteristics, the spectral linewidth and the peak wavelength stability as function of the injection current will be discussed. Moreover, the temporal stability of wavelength will be presented.

II. Wavelength-Stabilized Microbench Diode Laser System

As gain medium in the microbench diode laser system, a BA laser is used. The vertical structure of the device is similar to the structure reported in [4]. The active region is a GaInP single quantum-well embedded in AlGaInP waveguide layers. The n-side cladding layer was formed by AlInP whereas the p-side cladding is made of AlGaAs. The structure has a vertical far-field angle of 31° [full-width at half-maximum (FWHM)].

In the presented microbench, a BA laser with a total length of 2 mm and a stripe width of 100 μm was used. The lateral far-field width is 8° (FWHM). The facets were passivated. The front facet had a reflectivity of $R_f = 1\%$. The rear facet is antireflection (AR)-coated with $R_r \leq 10^{-3}$.

The amplified spontaneous emission (ASE) of the used device is given in Fig. 1. It can be seen that with the device the spectral range between 663 and 673 nm can be covered. The gain maximum has a typical thermal shift of 0.2 nm/K.

Fig. 2 shows a top view scheme of the microbench diode laser system. The BA gain medium is placed at Position 1. The resonator is formed by the front facet of the diode and the RBG. An RBG from OptiGrate with a diffraction efficiency (DE) of >99% and a specified spectral selectivity of $\Delta\lambda < 100$ pm (FWHM) at 671 nm was selected. The angle selectivity of the RBG at 671 nm is 2° (FWHM) at 671 nm given by the company. The RBG (4) has a dimension of length × height × width =

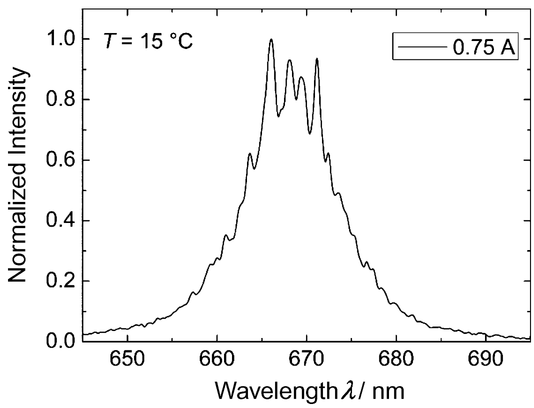

Fig. 1. Spectrum of the ASE at $T = 15$ °C and $I = 750$ mA.

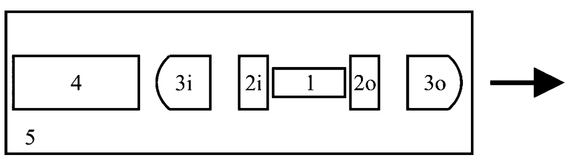

Fig. 2. Scheme of the microbench diode laser system: (1) BA laser; (2i, 2o) fast-axis collimator (FAC); (3i, 3o) slow-axis collimator (SAC); (4) RBG; (5) AlN-microbench (13 mm × 4 mm).

$(3.5 \times 2.5 \times 1.5)$ mm^3 and is placed on the rear side of the microoptical bench (4). It is made of photo-thermo-refractive glass with a typical thermal shift of the Bragg wavelength about 7 pm/K [5]. All microoptics include the RBG are AR-coated <0.3% for 671 nm. Based on the vertical and lateral far-field angles microcylindrical lenses from INGENERIC GmbH were selected to collimate the beam inside (i) and outside (o) the resonator. The fast-axis collimators on position (2i) and (2o) has a focal length of $f = 600$ μm with a numerical aperture (NA) of 0.8. The slow-axis collimators on position (3i) and (3o) were chosen with $f = 2300$ μm and NA $= 0.3$. With these microoptics and the above-mentioned BA device a residual divergence of 0.1° (FWHM) in the vertical and 2.5° (FWHM) in the lateral far-field was simulated based on beam propagation method of the second-order moments neglecting aberrations. This result to a beam mainly fits into the spatial acceptance angle of the RBG. This leads to an efficient feedback to the diode laser limited only by the DE of the RBG and the optical coupling efficiency.

The BA laser is mounted p-side down on CuW heat spreaders on the AlN-microbench (5). Position marks for the alignment of the microoptics are drawn by laser marking on the AlN-microbench. After active alignment the microoptics are fixed with UV-curable glue on the microbench. The lenses (2o) and (3o) form a collimated beam. The microbench has a footprint of (13×4) mm^2 and can be easily integrated as an excitation light source into mobile sensor platforms. For our experiments, this subassembly was mounted on a conduction cooled package (CCP) with a footprint of (25×25) mm^2. This system typically has a thermal resistance of 6.5 K/W.

III. Experimental Results

Fig. 3 shows the optical output power of the laser system mounted on CCP versus the injection current at a heatsink temperature of $T = 15$ °C. The threshold current is $I_{\text{th}} = 1.05$ A. Up to an output power of $P = 1$ W, the slope efficiency is $S = 0.75$ W/A. This results in a conversion efficiency of 19%. At an injection current of 3.5 A, a maximum output power of $P = 1.5$ W was achieved before rollover. With the above-mentioned thermal resistance of 6.5 K/W of the device, the gain maximum shifts 9 nm to longer wavelength at an injection current of 3.5 A. This results in a decrease in efficiency of the microbench laser due to a mismatch of the central wavelength of 671 nm provided by the RBG to the gain maximum of the BA laser at high temperatures.

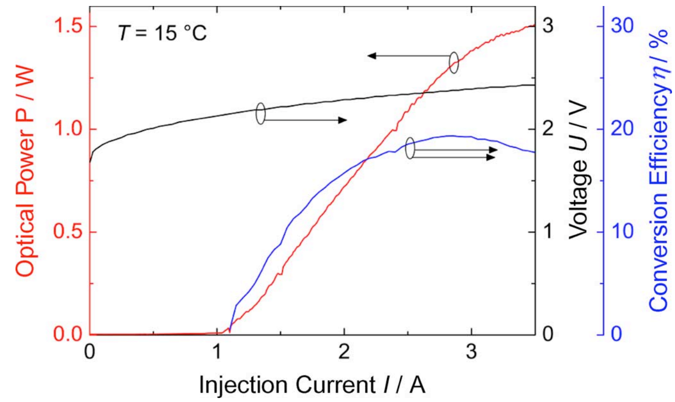

Fig. 3. Power–current–voltage characteristic of the microbench laser at $\lambda = 671$ nm and $T = 15$ °C.

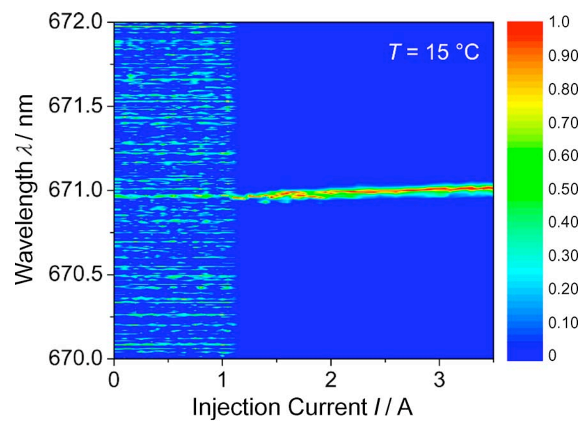

Fig. 4. Contour plot of optical spectra versus injection current of the microbench diode laser at $T = 15$ °C.

The optical spectra as a function of the injection current are presented in Fig. 4. They were measured with a double echelle monochromator (DEMON) from LTB Lasertechnik in Berlin GmbH with a spectral resolution of 9 pm. The data are presented in a contour plot up to an injection current of $I = 3.5$ A. Measurements were performed every $\Delta I = 50$ mA. The heatsink temperature was constant at $T = 15$ °C.

The intensity of each spectrum is normalized. At $P = 0.5$ W, the wavelength is 670.98 nm and increases to 671.02 nm at 1.5 W. This change of the output power causes only a peak wavelength shift of 40 pm. This meets the above-mentioned peak wavelength stability of excitation lasers for Raman spectroscopy. Using such a laser, it is possible to change the output

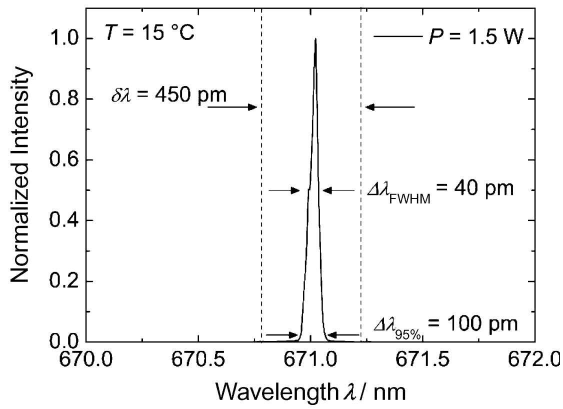

Fig. 5. Optical spectrum of the microbench diode laser at $P = 1.5$ W and $T = 15$ °C.

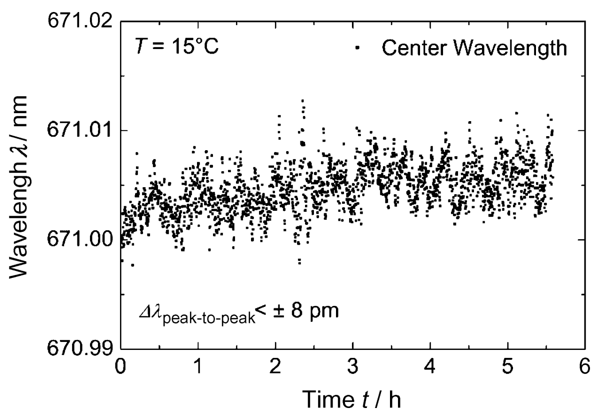

Fig. 6. Wavelength stability of the microbench diode laser over 5.5 h at $P = 1$ W and $T = 15$ °C.

power with respect to the substance under study without the necessity to recalibrate the Raman shift axis.

An individual spectrum at an output power of $P = 1.5$ W and a heatsink temperature of $T = 15$ °C is presented in Fig. 5. The intensity is normalized. At $\lambda = 671.0$ nm, a spectral width of $\Delta\lambda_{\mathrm{FWHM}} = 40$ pm and $\Delta\lambda_{95\%} = 100$ pm (95% power included) was achieved. This fits within the resolution of $\delta\lambda = 450$ pm and meets herewith the above-refereed demands for resolving Raman lines of most solid and liquid samples. A side-mode suppression ratio of 40 dB at $P = 1$ W and $T = 15$ °C was measured using a high dynamic optical spectrum analyzer Q 8384 from Advantest with a dynamic range >50 dB.

To test the capability of the devices for a calibration-free measurement over several hours, a wavelength stability test was performed and is presented in Fig. 6. During this measurement, the heatsink temperature of $T = 15$ °C was stabilized by a temperature controller 3040 of Newport with a long-term stability of 1 mK. The injection current was $I = 2.4$ A controlled by a laser diode driver 560 B of Newport with a long-term stability of 120 μA. The spectra were recorded every 10 s.

Over 5.5 h at an output power of $P = 1$ W, a wavelength stability of $\Delta\lambda_{\mathrm{peak-to-peak}} < \pm 8$ pm was achieved. The small drift to longer wavelengths of $\delta\lambda_{\mathrm{center}} \approx 5$ pm during the experiment may be caused by thermal heating of $\Delta T \approx 1$ K of the mounted RBG. After a time of about 3 h, the increase of the center wavelength saturates.

IV. Conclusion

We presented a compact wavelength-stabilized BA laser emitting at 671 nm on a microoptical bench. An RBG was used as a second resonator mirror for wavelength stabilization. At an injection current of 3.5 A, a maximum output power of 1.5 W with a spectral width of 40-pm FWHM was achieved. A wavelength stability of $\Delta\lambda_{\mathrm{peak-to-peak}} < \pm 8$ pm over 5.5 h was demonstrated to enable long-term application fields of the microbench laser (e.g., as an excitation light source for *in situ* Raman spectroscopy in mobile sensor systems).

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