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High power and high spectral brightness in 1060 nm α-DFB lasers with long resonators

K. Paschke, R. Güther, J. Fricke, F. Bugge, G. Erbert and G. Tränkle

Angled-grating DFB lasers with long resonators were fabricated and characterised at 1060 nm. 4 mm-long laser diodes showed a CW-output power of 3 W with a times-diffraction-limit factor $M^2 = 3.2$ and a spectral line width of 6 pm. A high spectral brightness of better than 1.2×10^4 MW/(cm^{2}sr nm) results.

Introduction: High-power continuous-wave laser sources with a high spectral brightness are required for spectroscopy and nonlinear optical frequency conversion. Among the monolithic semiconductor lasers, angled grating distributed-feedback lasers (α-DFB lasers) [1–3] compete with tapered laser diodes [4, 5] for high power and high spatial beam quality. In this Letter we present a high-power α-DFB laser having in addition a narrow spectral line width so that a high spectral brightness is obtained.

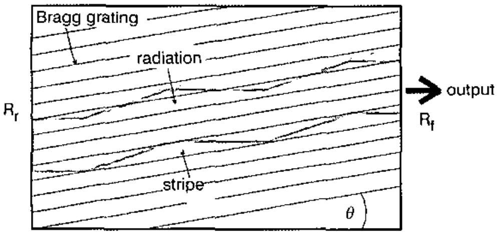
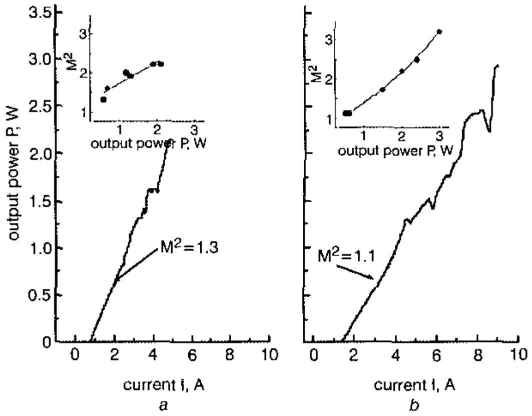


Fig. 1 *Schematic diagram of the α-DFB laser*

Device fabrication: α-DFB laser diodes incorporate a tilted Bragg-grating within the resonator favouring longitudinal and lateral single-mode emission [1–3]. Fig. 1 shows the scheme of a laser chip with the orientation of the Bragg grating, the *p*-electrode defined by lateral insulation, the snake shaped mode propagation of the radiation, and the high and low reflection (R_r and R_f) coated output facets. The layer containing an InGaAs quantum well embedded in a GaAs waveguide with a total thickness of 0.8 μm. Details of the structure and fabrication based on two-step epitaxy were described elsewhere [6]. The devices were mounted *p*-side down with CuW carriers on copper heatsinks. The optimum values of the slant angle ($\theta = 13.5°, \ldots, 15°$) and of the stripe width ($w = 115, \ldots, 160$ μm) were found by numerical simulation using a higher-order mode extension of the four-wave model [2]. They were experimentally verified.



a

b

Fig. 2 *CW light-current-characteristics of α-DFB lasers for resonator length L = 2 mm and L = 4 mm (slant angle θ = 15°, and stripe width 160 μm)*

a $L = 2$ mm
b $L = 4$ mm

Device characteristics: Fig. 2 compares the light-current-characteristics of two α-DFB laser diodes with different resonator length. Both laser diodes are characterised by a slant angle $\theta = 15°$, a stripe width $w = 160$ μm, and the facet reflectivities $R_r = 0.94$ and $R_f \leq 0.1$. The resonator length is $L = 2$ mm in Fig. 2*a* and $L = 4$ mm in Fig. 2*b*. The maximum output power of the 2 mm-long laser diode is $P = 2.2$ W. For $L = 4$ mm, the maximum output power reaches nearly $P = 3$ W. Therefore, larger length results in higher power.

The insets in Fig. 2 show the times-diffraction-limit factor M^2 obtained from the $1/e^2$-intensity levels in dependence on the emitted power. Even at high power emission in the range of a few watts, M^2 remains low. The M^2 values of 2.5 at the maximum power $P = 2.2$ W of the 2 mm-long laser diode (Fig. 2*a*) and of 3.2 at $P = 3$ W of the 4 mm-long laser diode (Fig. 2*b*), indicate that in both cases the fundamental mode dominates the higher-order modes. Thus, the lateral mode filtering mechanism is still maintained in this high power range. The emission is nearly diffraction limited until 0.7 W of the 2 mm-long laser diode in Fig. 2*a* and until 1.2 W of the 4 mm-long laser diode in Fig. 2*b*. The efficiency for $L = 2$ mm is 0.51 W/A. It decreases to 0.35 W/A for $L = 4$ mm. Altogether, the α-DFB lasers have a low M^2 also in the high power region of the light current characteristic quite comparable to a 1040 nm taper laser [4] and to a 735 nm taper laser [5].

Fig. 3 shows near and far fields for both resonator lengths. The Gaussian shape of the fundamental mode dominates the higher-order modes.

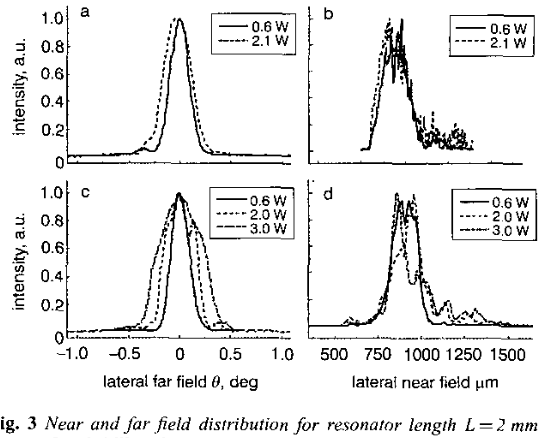


Fig. 3 *Near and far field distribution for resonator length L = 2 mm at powers P = 0.6 W, and P = 2.1 W and L = 4 mm up to P = 3 W*

a, b $L = 2$ mm
c, d $L = 4$ mm

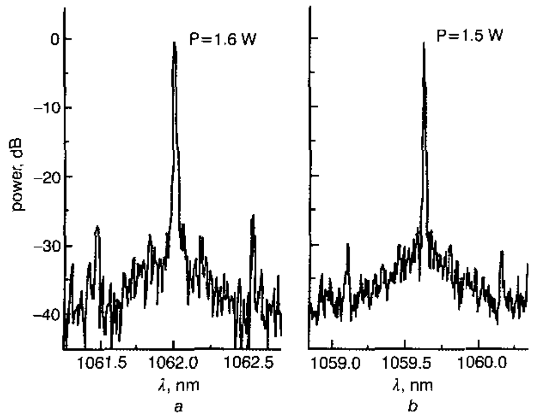


Fig. 4 *Spectral distribution of emitted radiation for resonator length $L = 2$ mm and $L = 4$ mm at power $P = 1.6$ W and $P = 1.5$ W, respectively*

a $L = 2$ mm
b $L = 4$ mm

The far field at $P = 3$ W for $L = 4$ mm (Fig. 3*c*) shows a stronger influence of higher-order modes compared to the far field at $P = 2.2$ W for $L = 2$ mm (Fig. 3*a*). The lateral near field is smoothed for the larger cavity length $L = 4$ mm (Fig. 3*d*) in comparison with the shorter resonator length $L = 2$ mm (Fig. 3*b*).

Fig. 4 compares both cases with respect to the spectral distribution of the emitted radiation at the power above which more than one longitudinal mode appears. For $L = 2$ mm, the device remains longitudinally singlemode up to $P = 1.6$ W and for $L = 4$ mm this holds up to $P = 1.5$ W. Resulting from the spectral resolution of the monochromator used the line width of the emitted radiation can be estimated to $\Delta\lambda_{FWHM} \leq 6$ pm. The sidemode suppression ratio is 27 dB in both cases. This confirms the high spectral selectivity of the α-DFB laser.

Finally, knowing the values of power, M^2, the wavelength and the spectral width, the spectral brightness β_λ of the α-DFB lasers can be calculated. With $P = 1.6$ W, $\lambda = 1060$ nm, $M^2_{vertical} = 1$, $M^2_{lateral} = 2$ and $\Delta\lambda_{FWHM} \leq 6$ pm we obtain the spectral brightness $\beta_\lambda = P/(M^2_{vertical}M^2_{lateral}\lambda^2\Delta\lambda) \leq 1.2\ 10^4$ MW/(cm^2 sr nm). This value is many times larger than the values reported for tapered laser diodes in [4, 5].

Conclusion: Long α-DFB lasers with a resonator length up to 4 mm are able to yield a high beam quality up to output power as high as 3 W. A longitudinal monomode spectrum is possible until a power of 1.6 W. The spectral line width smaller than 6 pm results in a high spectral brightness $\beta_\lambda \geq 1.2\ 10^4$ MW/(cm^2 sr nm).

Acknowledgments: This work was supported by the Deutsche Forschungsgemeinschaft (DFG) under the contract SE 954/1-2. The authors thank A.P. Bogatov, A.E. Drakin and A.A. Stratonnikov from the P.N. Lebedev Physical Institute, Moscow, Russia, for stimulating discussions.

6 January 2003
Electronics Letters Online No: 20030225
DOI: 10.1049/el:20030225

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High-power digitally tunable laser with integrated star coupler

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A novel scheme for a digitally tunable laser requiring only $P + Q + 1$ optical amplifiers for a device with in total $P \times Q$ wavelength channels is presented. A 32-channel InP/InGaAsP based device is fabricated. An optimised active layer and low on-chip losses result in a high optical output power.

Introduction: Digitally tunable lasers can be realised by monolithically integrating a waveguide grating router (AWG) and an array of semiconductor optical amplifiers (SOAs) into a single laser cavity. The first devices demonstrated required a separate SOA for each wavelength channel, thereby limiting the maximum channel count [1, 2]. In [3], an improved design was proposed, which reduced the total number of required SOAs to a number proportional to the square root of the total channel count. However, only a small fraction of the laser light in the cavity could be extracted, which limited the maximal obtainable output power. In this Letter we present a variation on this device, which allows for a considerable increase in output power and an improvement in the spontaneous emission noise suppression ratio.

Device structure: Fig. 1 shows the device that was presented in [3]. It consists of an N-channel AWG with, respectively, P and Q optical amplifiers connected to well-chosen positions at its input and output side and $N = P \times Q$. By turning on one of the P amplifiers at the input of the AWG and one of the Q amplifiers at its output, laser operation at in total $N = P \times Q$ different wavelengths could be obtained. (Note that in [3] the special properties of chirped AWGs were taken advantage of and therefore actually only an $N/2$-channel AWG was needed to obtain N different lasing frequencies. However, this is not relevant here and a similar approach could be used for the new device presented below). Unfortunately, the only waveguides shared by all N laser channels are those in the centre of the AWG. To extract the power out of the laser, one of the outer arms of the arrayed waveguide grating had to be used, resulting in a very low external efficiency (the output coupling ratio was estimated to be in the order of 1%). Using a booster amplifier, an average output power of -10 dBm could be obtained.

Two novel device geometries were proposed recently, which, similar to the device of [3], require only a number of SOAs proportional to the square root of the total channel count but allow for a higher output power [4, 5]. Both designs combine two separate AWGs in a single laser cavity. Here, we present a solution, which is a variation on the device proposed in [3] and requires only one AWG.

Fig. 2 shows the proposed device. The central part of the laser is identical to the device of Fig. 1 and still consists of an AWG surrounded by two amplifier arrays. However, to obtain access to all N wavelength channels, the outputs of one of the optical amplifier arrays are combined using a $1 \times Q$ star coupler. The latter can be integrated on