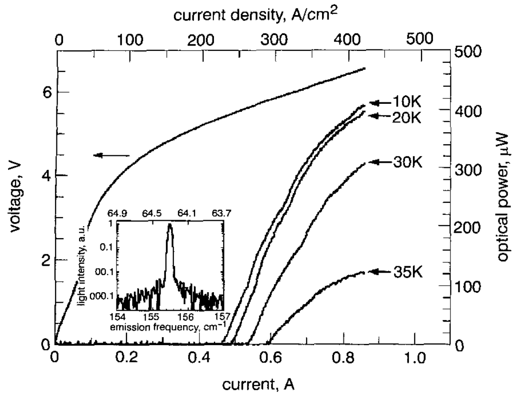

Fig. 2 *CW optical power from single facet and applied bias of 1.85 mm-long and 100 μm-wide laser stripe against drive current for various heatsink temperatures*

Inset: CW emission spectrum at drive current of 700 mA

The emission frequency ν of this far-infrared QCL can be tuned over a small range of a few cm^{-1} by changing the current and temperature. The CW spectral properties were analysed collecting the light by an off-axis parabolic mirror and sending it through an FTIR spectrometer (with a 0.09 cm^{-1} resolution) operated in rapid scan mode. The emission spectra (see one example in the inset of Fig. 2) collected at a constant heatsink temperature of 10 K and at various currents between 510 and 700 mA reveal a frequency tuning from 156.8 to 155.2 cm^{-1}. From Fig. 3 we can observe that at higher injection currents the main emission peak shifts discontinuously towards smaller energies. The reason for this behaviour is that between 510 and 600 mA the laser heats while maintaining the initial longitudinal mode. Between 600 and 650 mA as well as between 650 and 700 mA, modehops take place to the adjacent longitudinal mode. From this data, we extract the current tuning rate (0.3 A^{-1} cm^{-1}) and longitudinal mode spacing (0.62 cm^{-1}). From the latter and the known cavity length, we can also compute an approximate value for the group effective refractive index in the laser cavity. This procedure yields an $n_{eff} = 4.33$, which is in reasonable agreement with the value reported in the literature [5] including the dispersion correction ($n = 4.1$). Tuning of the laser is studied against tempeature at a fixed current of 700 mA. As shown in Fig. 3, the mode tunes, as expected, towards the red with a tuning rate of $1/\lambda\Delta\lambda/\Delta T = 1.9 \times 10^{-5}\,K^{-1}$.

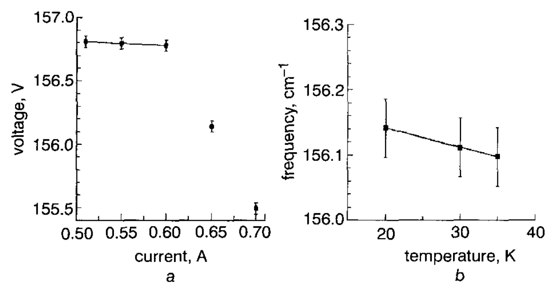

Fig. 3 *Peak position of CW spectra against injection current and temperature*

a Emission spectra measured at constant temperature of 10 K for various drive currents 510–700 mA

b Current kept at 700 mA and temperature varied between 20–35 K

Acknowledgments: We wish to thank L. Diehl and T. Aellen for fruitful discussions and encouragement. This work was supported in part by the European IST project WANTED and by the Swiss National Science Foundation.

21 October 2002

Electronics Letters Online No: 20021143

DOI: 10.1049/el:20021143

L. Ajili, G. Scalari, D. Hofstetter, M. Beck and J. Faist (*Institute of Physics, University of Neuchâtel, 1 A.-L. Breguet, CH 2000 Neuchâtel, Switzerland*)

E-mail: lassaad.ajili@unine.ch

H. Beere, G. Davies, E. Linfield and D. Ritchie (*Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom*)

References

1 FAIST, J., CAPASSO, F., SIVCO, D., SIRTORI, C., HUTCHINSON, A.L., and CHO, A.Y.: 'Quantum cascade laser', *Science*, 1994, **264**, pp. 553–556

2 KOHLER, R., TREDICUCCI, A., BELTRAM, F., BEERE, H., LINFIELD, E., DAVIES, G., RITCHIE, D., IOTTI, R.C., and ROSSI, F.: 'Terahertz semiconductor-heterostructure laser', *Nature*, 2002, **417**, pp. 156–159

3 ROCHAT, M., AJILI, L., WILLENBERG, H., FAIST, J., BEERE, H., DAVIES, G., LINFIELD, E., and RITCHIE, D.: 'Low-threshold terahertz quantum-cascade lasers', *Appl. Phys. Lett*, 2002, **81**, pp. 1381–1383

4 TREDICUCCI, A., CAPASSO, F., GMACHL, C., SIVCO, D.L., HUTCHINSON, A.L., and CHO, A.Y.: 'High performance interminiband quantum cascade lasers with graded superlattices', *Appl. Phys. Lett*, 1998, **73**, pp. 2101–2103

5 PALIK, E.D.: 'Handbook of optical constants of solids, gallium arsenide (GaAs)' (Academic Press Inc.), 1985, pp. 429–443

High-power ridge-waveguide distributed-feedback lasers emitting at 860 nm

H. Wenzel, M. Braun, J. Fricke, A. Klehr, A. Knauer, P. Ressel, G. Erbert and G. Tränkle

Data are presented describing distributed-feedback lasers emitting at 860 nm in a single transverse and longitudinal mode up to 300 mW. The lasers have a second order grating formed into an InGaP/GaAsP/InGaP multilayer structure embedded in the *p*-AlGaAs cladding layer.

Introduction: Single-frequency, single-spatial mode distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers have important applications in communication, spectroscopy and frequency conversion. Whereas for InP-based lasers in the 1300–1550 nm wavelength range the fabrication of integrated Bragg gratings using multi-step epitaxial techniques is well-established, it is more complicated for shorter-wavelength GaAs-based lasers. The achievement of an output power (P) of more than 100 mW is an additional challenge. Some years ago, a DBR laser was presented emitting 278 mW continuous wave (CW) output power at 856 nm [1]. Recently, 450 mW CW output power has been obtained with an InP-based DFB laser emitting at 1310 nm [2].

DBR lasers suffer from periodic nonlinearities in the light-current characteristics due to longitudinal mode hopping. In contrast, DFB lasers can operate in the same longitudinal mode over a large current range. Here, we will present DFB lasers emitting at 860 nm in a single transverse and longitudinal mode up to 300 mW.

Device structure and fabrication procedure: For lasers emitting in the desired wavelength region, AlGaAs or InGaAsP heterostructures can be employed. Owing to the high affinity of aluminium to oxygen, a surface of AlGaAs exposed to air can hardly be overgrown in a conventional metal-organic vapour phase epitaxy (MOVPE) reactor. However, the growth of AlGaAs is well established. For these reasons, AlGaAs is employed for the waveguide and cladding layers of the DFB lasers used in this study. The MOVPE of the structure stops after the growth of a first part of the *p*-cladding layer and an InGaP/GaAsP/InGaP layer sequence. After the second-order grating (period 262 nm) has been formed by holographic photolithography and wet-chemical etching into the Al-free layers on top of the wafer, the remaining part of the *p*-cladding layer and the *p*-contact layer is grown. The active layer consists of an InGaAs quantum well sandwiched between GaAsP spacer layers. Lateral optical confinement is provided by a 3 μm wide ridge-waveguide (RW) with an effective-index step of $\Delta n_{eff} = 0.005$. The device structure and fabrication procedure is similar to that of the RW Fabry-Perot lasers described in [3]. The cavity length is $L = 1.5$ mm and the front and rear facets are anti- and high-reflection coated, respectively.

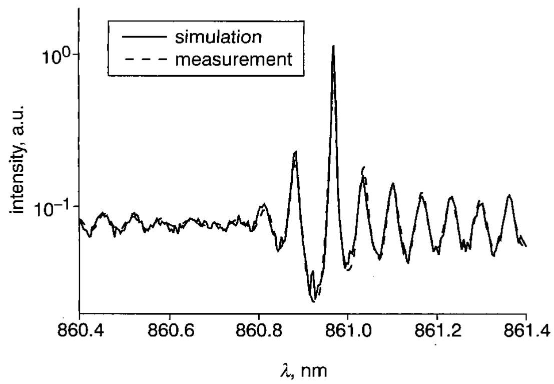

Fig. 1 *Emission spectrum of DFB laser below threshold*

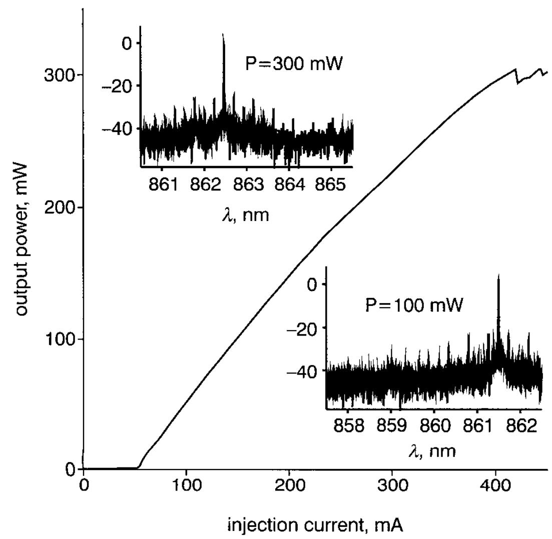

Fig. 2 *Light-current characteristic of DFB laser under CW operation at 25°C heat sink temperature*

Inset: Optical spectra recorded in dBm

Results: The emission spectrum measured below threshold is shown in Fig. 1. By fitting the measured spectrum to a simulated one, besides other parameters a complex valued coupling coefficient $\kappa = (1.5 + i0.15)\,\text{cm}^{-1}$ of the Bragg grating and a front facet reflectivity of 0.01% has been determined. Fig. 2 shows the CW light-current characteristic of a laser mounted *p*-up on an AlN submount. The temperature of the copper heatsink is maintained at 25°C. The threshold current is about 50 mA and the slope efficiency, for $P < 150$ mW, is as high as $\Delta P/\Delta I = 1$ W/A. The laser achieves a maximum power of 303 mW before a kink occurs. Optical spectra of the laser are depicted in the inset of Fig. 2. The side mode suppression ratio is at least 30 dB. The side peaks are caused by the optical spectrum analyser used. Note that the longitudinal mode spacing beside the stop band is only 67 pm. From the increase of the lasing wavelength of $\Delta\lambda = 1$ nm from $P = 100$ mW to $P = 300$ mW a temperature rise of $\Delta T = 16$ K can be deduced. The lateral far-field profiles are shown in Fig. 3. The full width at half-maximum (FWHM) of the lateral far-field decreases from 7.9° at $P = 100$ mW to 7.4° at $P = 200$ mW and finally to 6.2° at $P = 300$ mW. The excellent symmetry and lack of beam steering indicates the high spatial mode purity of the lateral far-field in addition to the high spectral purity of the lasing emission. The vertical far-field plotted in the inset has a FWHM of only 20.7° independent from the power. In Fig. 4 results of a lifetime test are shown. Five lasers mounted *p*-up on AlN submounts were aged over a time period of 3000 h at a heatsink temperature of $T = 25$°C and a constant power of $P = 250$ mW. The degradation rates of all devices obtained from a linear fit are below 5×10^{-6}/h.

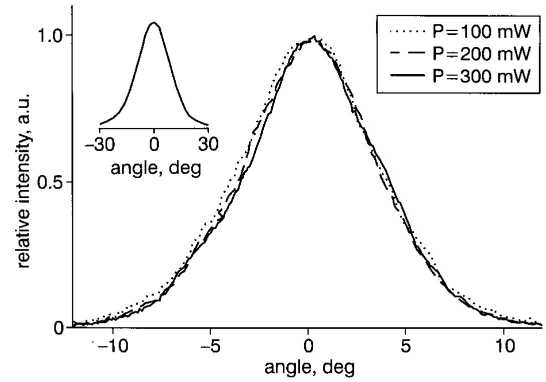

Fig. 3 *Normalised lateral far-field profiles of device of Fig. 1*

Inset: Vertical far-field profile

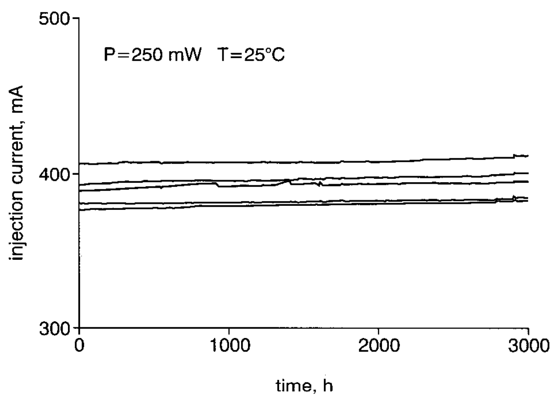

Fig. 4 *Aging test of five lasers driven at constant output power*

Conclusions: We have demonstrated singlemode operation of 860 nm RW DFB lasers up to a CW output power of 300 mW. The Bragg grating integrated into the active cavity did not deteriorate the long-term reliability.

Acknowledgment: This work has been supported by the 'Bundesministerium für Wirtschaft und Technologie' through contract KF 0088202 KFK 0.

5 September 2002
Electronics Letters Online No: 20021145
DOI: 10.1049/el:20021145

H. Wenzel, M. Braun, J. Fricke, A. Klehr, A. Knauer, P. Ressel, G. Erbert and G. Tränkle (*Ferdinand-Braun-Institut für Höchstfrequenztechnik, Albert-Einstein-Str. 11, 12489 Berlin, Germany*)

References

1 MAJOR, J.S., O'BRIAN, S., GULGAZOV, V., WELCH, D.F., and LANG, R.J.: 'High-power singlemode AlGaAs distributed Bragg reflector laser diodes operating at 856 nm', *Electron. Lett.*, 1994, **30**, pp. 496–49

2 MENNA, R., KOMISSAROV, A., MAIOROV, M., KHALFIN, V., TSEKTOU, A., TODOROV, S., CONNOLLY, J., and GARBUZOV, D.: 'High power single spatial and longitudinal mode 1310 nm InGaAsP/InP Lasers'. 27th ECOC, Amsterdam, 2001, Tu.B.1.6

3 BEISTER, G., BUGGE, F., ERBERT, G., MAEGE, J., RESSEL, P., SEBASTIAN, J., THIES, A., and WENZEL, H.: 'Monomode emission at 350 mW and high reliability with InGaAs/AlGaAs ($\lambda = 1020$ nm) ridge waveguide laser diodes', *Electron. Lett.*, 1998, **34**, pp. 778–779