In the inset to Fig. 3, we plot the logarithm of the ratio of the signal strengths of the two links against time. This is a measure of the difference in their optical losses and peaks at a value of 25 km^{-1}, which is 250 times larger than the calculated value between wavelength of 8 and 1.3 μm for a condition of typical haze (visibility 10 km) [9]. The superior performance of the QC laser link compared to the near-IR link can readily be understood from the wavelength dependence of Rayleigh- and Mie-scattering. The particular shape of the curve in the inset of Fig. 3 is related to the size and distribution of water droplets in the air and changes with fog density and structure over time. The mid-IR link is much less affected by these fluctuations owing to the considerably longer wavelength. This effect can also be seen from the smaller intensity fluctuations of the QC laser link over time (see particularly at around 4.20 a.m.).

Conclusion: We demonstrated that QC lasers can be used to transmit complex data streams through the atmosphere and with clearly greater reliability than near-IR links under conditions of poor visibility.

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High-brightness 735 nm tapered diode lasers

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High brightness 735 nm single emitter tapered diode lasers were manufactured and analysed. A beam propagation factor M^2 smaller than 1.4 is achieved up to an output power of 2 W.

Introduction: There is increasing demand for high brightness diode lasers in the spectral range 715–780 nm. Examples of applications are photodynamic therapy (PDT) and pumping of solid-state lasers. In addition to high output power, high brightness is required. This corresponds to the demand for nearly diffraction-limited beams with a small beam propagation factor M^2.

Broad area (BA) diode lasers for this spectral region reach maximum output powers of several watts based on AlGaAs or InAlGaAs quantum wells (QWs) [1–3] and Al-free InGaAsP QWs [4]. Tensile-strained GaAsP QWs embedded in AlGaAs were applied by our group for the manufacturing of reliable diode lasers near 735 nm with degradation rates below $5\times10^{-5}\ \mathrm{h}^{-1}$ at 2 W output power from a 100 μm stripe over 2000 h [5].

Broad area devices with a stripe width of about 100 μm suffer from poor beam quality. Typical beam divergences ($1/e^2$-values) are at least 10 times larger than the diffraction limit, i.e. $M^2 > 10$. A possible solution to overcome this limitation is the use of tapered lasers consisting of an index-guided straight section and a gain-guided tapered section. For the wavelength range 980–1550 nm the approach has been successfully realised [6–9].

In this Letter we present tapered lasers optimised for the wavelength range around 735 nm. Details of the structure, as well as the light-current characteristic, beam quality and spectral properties are reported.

Laser structure: The laser structure is similar to that presented in [5]. The epitaxial layers were grown by low pressure MOVPE on (100) n-GaAs substrates. The active $GaAs_{0.67}P_{0.33}$ QW with a thickness of 9 nm is embedded in $Al_{0.65}Ga_{0.35}As$ waveguide and $Al_{0.70}Ga_{0.30}As$ cladding layers. The layer sequence is completed by a highly doped p-GaAs contact layer.

The tapered laser consists of an index-guided straight section and a gain-guided tapered section. The index guiding is achieved by a ridge waveguide (RW) formed by reactive ion etching and depositing of an insulator (Al_2O_3) on the etched surface. The ridge width was chosen to be $W_{RW} = 3$ μm. In the tapered section, the contact layer outside of the p-electrode is removed by wet chemical etching to reduce current spreading. The metallisation on the p-side contact was formed by evaporating a Ti-Pt-Au multilayer and by electro-plating a thick Au layer. After thinning and n-metallisation the wafer was cleaved to obtain a total cavity length of $L = 2.5$ mm.

The front facet was antireflection coated ($R_f \simeq 1\%$), the rear facet was high-reflection coated ($R_r \simeq 94\%$). The lasers were mounted p-side (epi-side) down on CuW submounts. All devices were soldered with AuSn using a procedure also applied for BA lasers [5]. The n-side was contacted by wire bonding.

To keep the processing of the lasers as simple as possible, no cavity-spoiling grooves for transverse-mode filtering were used since they would require an additional etch step and an additional planarisation for epi-side down mounting. Instead, the length L_{RW} of the RW section and the full angle φ_{TR} of the tapered section were carefully optimised. The highest brightness was obtained for values $L_{RW} = 1000$ μm and $\varphi_{TR} = 6°$.

Results: A typical power–voltage–current characteristic is shown in Fig. 1. The threshold current is ~500 mA; the slope efficiency has a value of ~1.0 W/A slightly above threshold. Comparing these values with those of a BA laser made from the same epitaxial material having a stripe width of 100 μm, the threshold current is comparable but the slope efficiency of the tapered laser is only ~83% owing to the additional radiation losses caused by the tapered cavity. Nevertheless, the conversion efficiency for the tapered laser reaches almost 45% at 1 W. A maximum output power of 3.3 W was obtained at an injection current of 5 A.

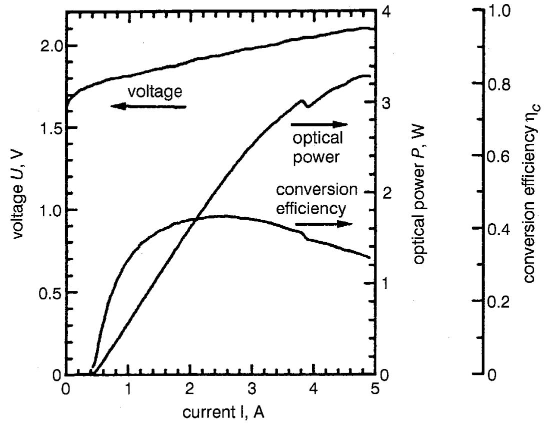

Fig. 1 *Power–voltage–current characteristic of tapered diode laser*
$T = 25^\circ$C; $L = 2.5$ mm, $W_{\mathrm{RW}} = 3$ µm, $L_{\mathrm{RW}} = 1000$ µm, $\varphi_{\mathrm{TR}} = 6^\circ$, $\lambda = 735$ nm

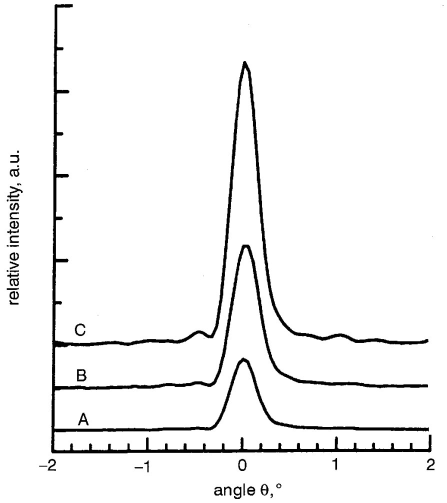

Fig. 2 *Effective lateral far field for tapered diode laser*
Device parameters same as Fig. 1
A: output power $P = 0.5$ W
B: $P = 1$ W
C: $P = 2$ W

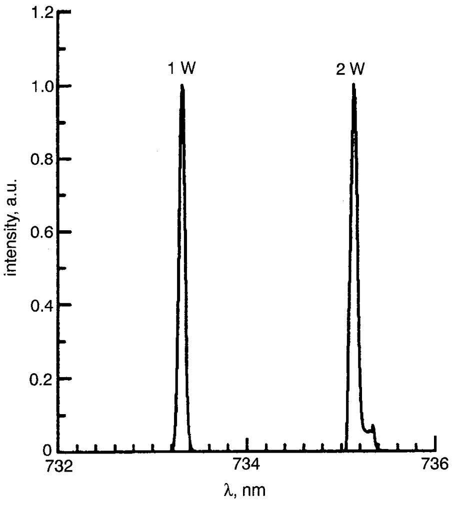

Fig. 3 *Emission spectrum of tapered diode laser at 1 and 2 W optical output power*
Device parameters same as Fig. 1

The position of the beam waist and the intensity profiles in the beam waist, at the front facet and in the far field, was measured applying the method of the moving slit (ISO 11146, Annex A). Based on measured intensity profiles, the beam propagation factor M^2 was calculated. The beam widths required to calculate M^2 were identified with the $1/e^2$ widths of the intensity profiles in the beam waist and in the far field.

Typically, at 2 W the M^2 values are smaller than 1.6 for all devices, reaching $M^2 = 1.4$ for the best device. These data illustrate the nearly diffraction limited properties of the lasers. The effective far field for the best laser is given in Fig. 2. The far-field angle (full width at $1/e^2$ maximum) is $<0.56^\circ$. At $P = 0.5$ W 90% of the output power is concentrated within a full angle of $<0.64^\circ$, at 1.0 W $<0.75^\circ$ and at 2.0 W $<0.94^\circ$. Owing to this high brightness an effective coupling of the laser light into a fibre can be readily realised.

Finally, the spectral properties of the lasers are discussed. Fig. 3 shows the measured intensity spectra. At 1 W output power the central emission wavelength is $\lambda = 733.3$ nm and at 2 W $\lambda = 735.1$ nm. In either case the spectral width (full width at half maximum) is <0.2 nm.

Conclusion: High-brightness lasers having a straight ridge waveguide section and a gain-guided tapered section emitting at 735 nm were manufactured. The record low M^2 value of 1.4 at 2.0 W output power reveals the near-diffraction limited beam properties. Together with their spectral features, these types of diode lasers are promising for medical applications, the pumping of solid-state lasers and, owing to the small spectral bandwidth, for nonlinear frequency conversion.

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