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Investigation of the mode structure of InAsSb/InAsSbP lasers with respect to spectroscopic applications

A. Popov[a], B. Scheumann[b], R. Mücke[b], A. Baranov[a], V. Sherstnev[a], Y. Yakovlev[a], P. Werle[b,*]

[a] *Ioffe Physico Technical Institute, 194021 St. Petersburg, Russia*
[b] *Fraunhofer Institut IFU, Kreuzeckbahnstr. 19, 82467 Garmisch-Partenkirchen, Germany*

Abstract

New InAsSb diode lasers in the 3.4 μm spectral region were tested for their suitability for trace gas analysis. Selected lasers have shown single-frequency lasing over a large range of current and temperature and a cw optical power of 2 mW/facet at 82 K. The operating temperature range was 77–105 K under driving currents of 30 to 250 mA. The tuning characteristics of the investigated lasers were about 1 GHz/mA and 1.3 $\mathrm{cm^{-1}/K}$.

1. Introduction

Tunable diode laser absorption spectroscopy (TDLAS) is increasingly being used to measure atmospheric trace gas concentrations down to low ppbv levels (10^{-9} volume mixing ratio). This optical technique is selective and sensitive and, therefore, fulfills the requirements for trace gas analysis in the atmosphere for most of the smaller molecules with resolved absorption spectra [1]. One limiting factor for ultra-sensitive measurements is the excess noise of the lasers, which varies depending on the mode structure of the emitted light [2]. Commonly IV–VI (lead-salt) compound lasers are used for TDLAS in mid-infrared [3]. In this paper III–V (InAsSb) lasers [4,5] manufactured at Ioffe Physico Technical Institute, are investigated for their suitability for trace gas monitoring. Optical output power, mode structure, tuning characteristics and beam profile will be discussed.

The laser double heterostructure (DH) was grown by liquid-phase epitaxy (LPE) [7] on an [100] oriented InAs substrate (Fig. 1). A 1 μm thick area (calculated band gap energy E_g of 365 meV at 77 K, refractive index 3.54) was lattice-matched between two 2.5 μm thick InAsSbP confining layers (E_g was 550 meV). For index-guiding [6], the refractive index differed between active and cladding layers by 0.02. The cap was a 1 μm thick InAs layer. To avoid dislocation formation, the lattice mismatches between the layers and the substrate were less than 0.001. The carrier concen-

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*Corresponding author.

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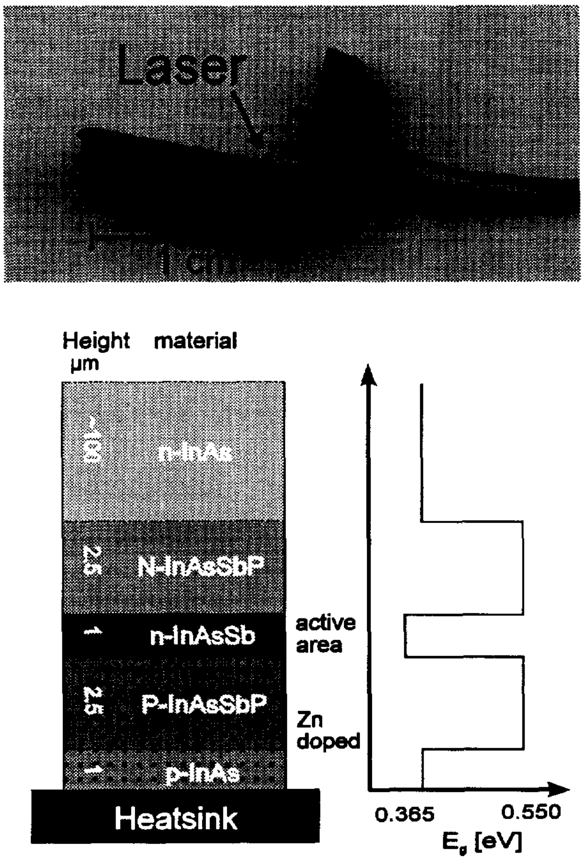

Fig. 1. Electrical and mechanical layout of the DH-Laser structure as grown by liquid phase epitaxy (LPE) at Ioffe Institute. The overall physical dimensions of the laser chips are 280 × 500 µm.

tration in the nominally undoped active and n-confining layers was $10^{16}\,cm^{-3}$. The p-type confining and cap layers were doped with Zn up to $10^{18}\,cm^{-3}$. The 14 µm broad deep-mesa-stripe chips were fabricated by photolithography and chemical etching. The substrate was lapped to 100 µm thickness. The 280 µm cavity length lasers with uncoated facets were mounted on the special type copper heat sink. The substrate and stripe contact were metallized with AuAg providing a good series resistance as low as 1.6 Ω.

2. Experimental setup

To test lasers for their suitability for trace gas measurements, an automated test setup has been developed at the Fraunhofer Institute in Garmisch-Partenkirchen [7], which allows automatically recording of laser optical power, mode structure and noise wideband characteristics over a broad range of current and temperature. A schematic layout is shown in Fig. 2. The laser was mounted in a LN_2-cooled Dewar (Laser Photonics, model L5736), temperature and current stabilized over the range from 77 to 120 K and between 0 and 300 mA (with ILX Lightwave LDC 3742 power supply), mounted on *xyz*-stage for focus-alignment. An off-axis parabolic mirror (OAP) with 25 mm diameter was used to collimate the laser output beam. Electrically actuated mirrors were used to pass the beam through the various elements. The mirror could be placed on a calibrated pyroelectric power meter (Laser Precision, model RS 5900) or steered, through or around a $\frac{1}{2}$ meter monochromator (Digikröm 480). Another mirror was used to switch between a HF detector (SAT, HgCdTe, 200 MHz bandwidth), combined with a preamplifier (SAT IR 500) and a spectrum analyzer (Marconi SA 2383), for noise measurements, or a chopper (SR 540) and LF detector (Polytec HCT 70), combined with a lock-in amplifier (SR 530), for relative power measurements (mode structures). A HeNe-laser was coupled into the system by a removable beam-splitter to pre-align the whole system. A problem did arise, the InAsSb lasers have a much larger half-width emittance angle than commonly used lead-salt lasers. Because of the limited size of the OAP (25 mm diameter at 32 mm focal length), a separate "external" optical output power measurement with a 25 mm BaF_2 lens was made to get the full emitted power on the meter. The laser field patterns were recorded by a pyroelectric camera placed directly in front of the laser (without optics).

3. Results

Several lasers in the 3 µm spectral range have been tested. In this paper we present spectral

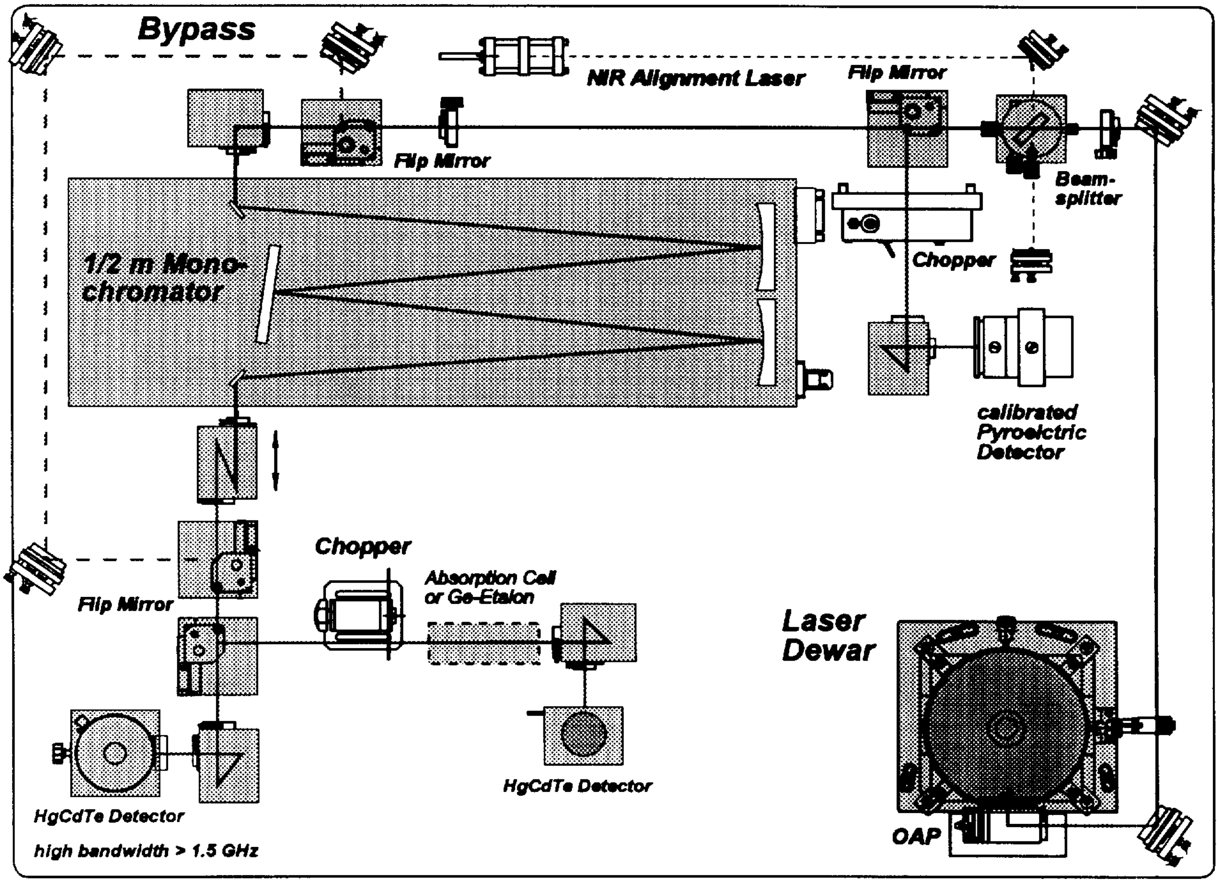

Fig. 2. Computer-controlled test equipment for semiconductor diode lasers developed at Fraunhofer Institute. Mode maps, tuning characteristics, optical noise and power can be recorded automatically over wide ranges of operating temperature and injection current.

Characteristics of a selected laser as an example. The lasers have been tested over a wide current range (25–250 mA) and temperature (77–105 K) range. The threshold current I_{th} was 28 mA at 77 K. The threshold current increased with temperature exponentially. The characteristic temperature T_0 [6] was calculated to be 20 K. Detailed measurements of the lasing spectra show that lasing occurs in a single longitudinal mode over a wide temperature and current range. As an example the spectra of the laser at one temperature are presented here (Fig. 3). For a quantitative characterization of the lasers the "*spectral purity*" (SP) has been introduced. It is a quantitative parameter reflecting the spectral purity of the tested laser calculated by

$$\mathrm{SP} = 100 \sum_i \left[\frac{P_i}{P} \right]^2 \quad [\%],$$

where P_i is the power of a separated mode and P is the overall power. Contrary to lead–salt lasers lasing was observed without mode-hopping over a wide current range. We observed mode jumps which corresponded to an energy higher than the longitudinal mode spacing and which increased with temperature from 4 cm^{-1} at 77 K to 20 cm^{-1} at 100 K. For tunable laser spectroscopy, the tuning rate is a very important

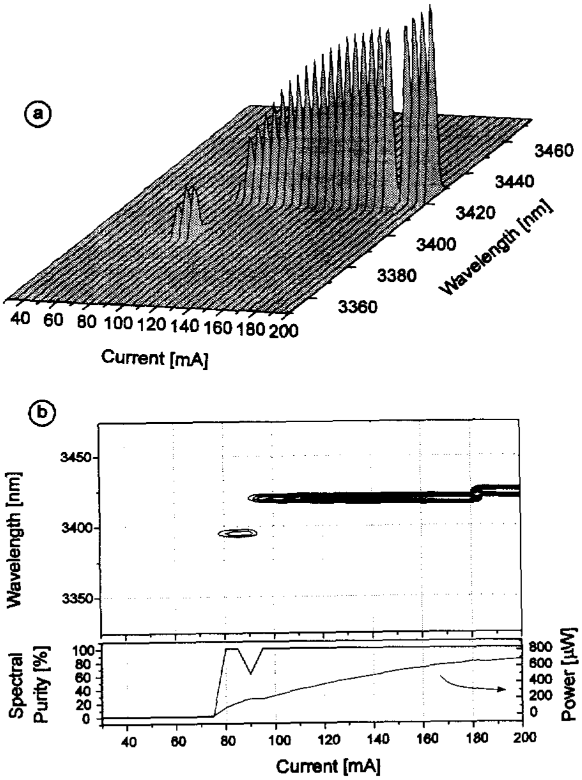

Fig. 3. (a) A mode map of the DH-laser at 95.5 K heatsink temperature and (b) total power and spectral purity demonstrate single-frequency operation without significant spontaneous emission.

parameter (Fig. 4). The coarse tuning of the main mode by temperature was 1.3 cm^{-1}. The current tuning characteristic was calculated to be 0.98 MHz/mA. The overall tuning range was 50 cm^{-1} by temperature (77–105 K). The large continuous tuning range by current (over 1.2 cm^{-1} under a current between 30 and 200 mA) is very attractive for spectroscopic applications.

For the use of multi-pass cells, the beam profile is a design factor for the collimating optics. An example of the beam profile of the laser tested is shown in Fig. 5a. The emitted power is nearby Gaussian with an elliptic factor of only 1.7. With a Gaussian fit, the divergence (at FWHM) can be estimated to be 30 deg parallel and 50 deg perpendicular to the junction plane. Since the laser beam has a large divergence (30/50 deg FWHM), the optical power has been measured separately. Therefore, a 25 mm BaF_2 lens was used to collect the radiation on a power meter. By this measurement, 2 mW/facet CW power has been obtained at 200 mA drive current and a temperature of 80 K (Fig. 5b). The quantum efficiency near threshold was 5% (11 µW/mA) and decreased down to 3% (7 µW/mA) at 3 times threshold current.

4. Summary

Novel mid-infrared III–V semiconductor lasers emitting in the 3.4 µm range have been investigated with respect to spectroscopic applications. The lasers are InAsSb double heterostructure grown by LPE. They have been tested between 77 and 105 K under 30–250 mA DC injection current. They have demonstrated single-frequency lasing with optical power as high as 2 mW per facet. The temperature and current tuning were 1.3 cm^{-1}/K and 0.98 MHz/mA. The overall tuning range was 50 cm^{-1} by temperature

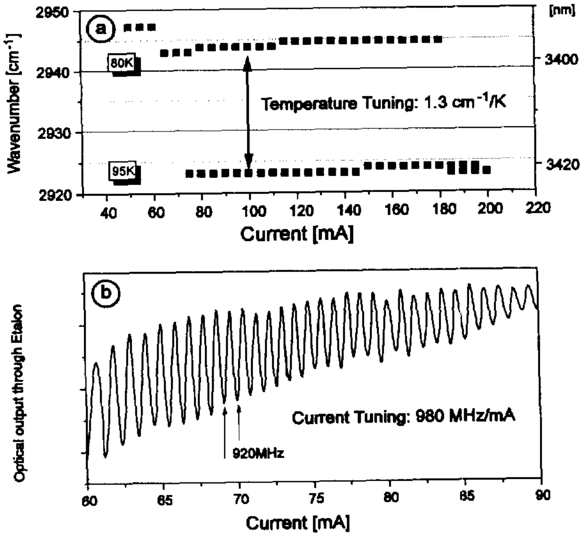

Fig. 4. (a) Tuning characteristics of the laser vs. injection current for different heat sink temperatures and (b) optical output through a Ge- étalon.

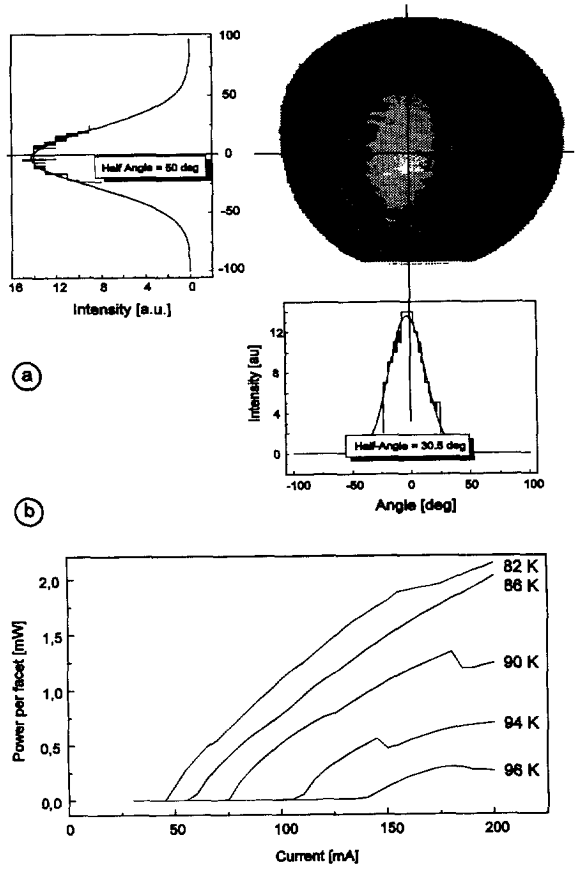

Fig. 5. (a) Beam profile measured in the direction of the two axes of the ellipse with a pyroelectric camera. The distance between the laser facet and the camera was 30 mm. The FWHM angles are 50 and 30 degrees. (b) Output power vs. current and temperature.

(77–105 K). With these characteristics such lasers seem to be suited for many spectroscopic applications. Especially the single mode power of more than 1 mW is very attractive for high frequency modulation spectroscopy [1]. Nevertheless careful selection of laser devices is necessary and, therefore, future work has to be done to improve the quality of these novel devices, which look very promising for sensitive trace gas analysis.

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