# Phase-locked InGaAsP laser array with diffraction coupling

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A phase-locked array of InGaAsP lasers has been fabricated for the first time. This 50-$\mu$m-wide array utilized diffraction coupling between adjacent lasers to achieve phase locking. Threshold current as low as 200 mA is obtained for arrays with 250-$\mu$m cavity length. Smooth single-lobe far-field patterns with beam divergence as narrow as 3° have been achieved.

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Phase-locked injection laser arrays have recently gained increasing attention.[1-8] The phase array consists usually of a number of spatially separated coherent sources which are phase coupled by some means (e.g., external cavity,[1,2] evanescent waves,[3] overlapping modes,[4] and coupling stripes[5]). These devices can produce laser beams with very narrow angular divergence as well as high output power. In addition, the laser beam can be directed by electrically varying the relative phase and amplitude between individual lasers. In optical communication, these phase array injection lasers are therefore desirable in coupling light sources to fibers. The InGaAsP/InP laser is especially favorable since it can emit in the 1.1–1.6-$\mu$m wavelength range which matches the low loss and low dispersion wavelength range of present fibers. In this letter we report the first InGaAsP phase-locked laser array. A diffraction coupling mechanism[8] is used here to phase lock the individual stripe lasers.

A schematic representation of the phase array is shown in Fig. 1. The structure consists of three sections. The ten modified stripe lasers with equal lateral spacing occupy in the central section of the device. The two end sections allow the individual beams to diffract and "mix." The length of the central section is $\sim 100\,\mu$m and the end sections are 50–100 $\mu$m long. Each individual laser stripe is $\sim 3\,\mu$m wide with 2-$\mu$m separation between adjacent stripes. A cross section of the laser stripes is also shown in Fig. 1.

The device involves four conventional liquid phase epitaxial (LPE) layers grown on $N^+$-InP substrate. The composition and thickness of the LPE layers are as follows: $N^+$-InP confining layer (3 $\mu$m thick, Sn doped to $\sim 2\times 10^{18}$ cm$^{-3}$), InGaAsP active region (0.2 $\mu$m thick, undoped, background electron concentration is $\sim 4-9\times 10^{16}$ cm$^{-3}$), $P^-$-InP confining layer ($\sim 2\,\mu$m thick, Zn doped to $2-5\times 10^{18}$ cm$^{-3}$), and $P^+$-InP or $P^+$-InGaAsP cap layer (0.2 $\mu$m, Zn doped to $2\times 10^{18}$ cm$^{-3}$). After growth, $Si_3N_4$ is deposited on the wafer and 10 stripe openings are made in the [01$\bar{1}$] direction. On the central section, the $P^+$-InP and $P^-$-InP layers are etched with iodic acid through the stripe openings. The etching is direction dependent and produces V-shaped grooves having a depth of $\sim 0.7\,\mu$m. After etching, the nitride is removed, a layer of $SiO_2$ is deposited on which $\sim 50$-$\mu$m-wide stripes are opened over the sections containing the stripe lasers. Then, AuZn/Au and AuGe/Au contacts are evaporated on the top and bottom sides of the wafer, respectively. As the metal semiconductor contact resistance is higher for the $P^-$-InP than for the $P^+$-InP, most of the current is injected through the top stripes rather than through the V grooves. This periodic injection profile in the central section gives rise to maximum gain in the active layer beneath the stripes. Upon leaving the central section, the beams from the individual stripes spread out diffractively and, upon reflection from the end mirrors, couple with each other. Considering the emission wavelength of the present laser (1.2 $\mu$m) and the beam divergence in the 50–100-$\mu$m diffraction section, a substantial overall coupling between the 10 individual lasers is expected. In most other arrays with wide separation between individual lasers, the coupling takes place only between adjacent stripes. For the present array having 3-$\mu$m-wide stripes with 2-$\mu$m separation, the modal overlap between the adjacent laser stries in the central section provides further direct coupling. The combined effect is strong phase locking.

The threshold currents of the phase-locked laser array are $\sim 300$ mA, with the lowest being 200 mA. The differential quantum efficiency of these lasers is $25 \pm 5\%$ for both

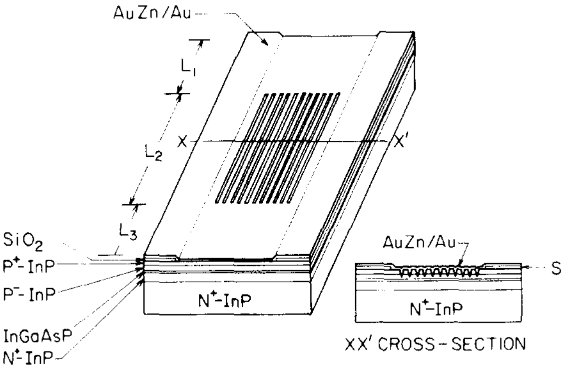

FIG. 1. Schematic diagram of the diffraction-coupled array.

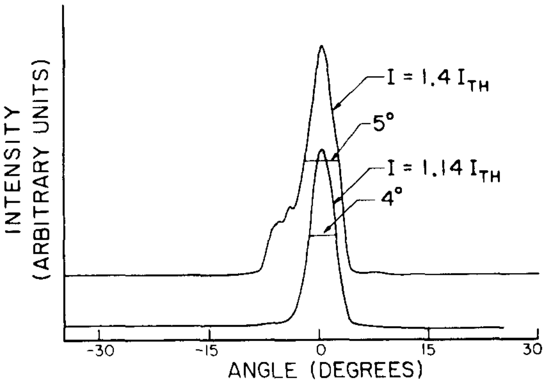

FIG. 2. Typical far-field patterns of the array lasers.

facets. An output power of 210 mW (limited by the pulse generator) is obtained with 100-ns pulses. The far-field patterns are taken with a fixed Ge photodiode (2 mm wide) placed 1 m away from a rotatable probe station on which the laser is mounted. The angular resolution of this configuration is about 0.2°. The lasers show single-lobe far-field patterns; beam divergence (full width at half-maximum) as narrow as 3–5° has been obtained (Fig. 2) up to 40% above threshold. Compared with previous published work, the present laser array possesses a smooth far field which is free from multiple peaks. However, the layer nonuniformity from liquid phase epitaxial growth results in differing stripe operating levels above threshold current. This leads to near-field spots with nonuniform spot size giving rise to a far-field divergence which is slightly wider than that expected from a 50-$\mu$m array.

In conclusion, a diffraction-coupled phase-locked InGaAsP laser array has been fabricated. Smooth single-lobe far-field patterns with narrow divergence (3°) have been achieved.

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# Reliability of constricted double-heterojunction AlGaAs diode lasers

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Constricted double-heterojunction diode lasers have been life tested at 70 °C heatsink temperature and 3–4 mW/facet in cw operation. A median life of 7800 h is obtained at 70 °C, which extrapolates to $4\times10^5$ h median life at room temperature. The extrapolated mean time to failure at room temperature is in excess of $10^6$ h. Single-longitudinal-mode cw operation is maintained after 10 000 h of accelerated aging at 70 °C.

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Constricted double-heterojunction (CDH) lasers are mode-stabilized devices grown by one-step liquid phase epitaxy (LPE) over channeled substrates.[1] We have reported previously on their cw operational characteristics[1–3], which include very low threshold-current temperature sensitivity[2] as well as lasing up to 170 °C,[3] the *highest* heat-sink temperature ever reported for cw operation of a semiconductor diode laser. Here we report on reliability tests which place CDH devices on a par with the best results for AlGaAs devices.[4–6] A median life of 7800 h is found at 70 °C, which extrapolates to 45 years of median life at room temperature when a 0.7-eV activation energy is considered. Furthermore, the single-mode character of CDH devices (i.e., single-longitudinal-mode cw operation and fundamental-spatial-mode operation) is maintained after 10 000 h of accelerated aging at 70 °C. This represents the longest reported diode-laser lifetime in single-longitudinal-mode operation.

The CDH laser structure which was life tested is of the "ridge-guide" type[1,7]; that is, a device with a convex-lens-shaped active layer above a substrate mesa (see Fig. 1). Such devices have been shown to be single mode in cw operation to cw power levels as high as 7 mW/facet, and to have threshold-current temperature coefficients $T_0$ in the 180–400 °C range.[1,2,7] Ten devices from two CDH wafers were placed on life test at power levels between 3 and 4 mW. Threshold currents were between 60 and 100 mA, and the initial thermal resistances were between 25 and 40 °C/W. The lasers were mounted with In solder on Cu heatsinks, and had ($\lambda$ /2) $Al_2O_3$ passivation coatings[8] on the emitting facets and dielectric-stack reflecting coatings[9] on the rear facets. The de-

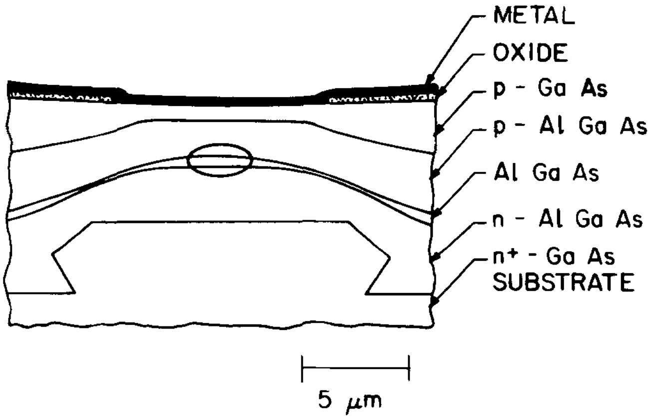

FIG. 1. Schematic representation of the CDH laser structure.