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## High Performance $10^0$ Angle-Facet Laser Amplifiers

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The first  $10^0$  angle-facet semiconductor laser amplifiers (SLA's), with facet reflectivities as low as  $10^{-5}$  are described. These reflectivities improve the  $10^{-4}$  obtained for  $7^\circ$  angle-facet SLA's [1], [2]. Further, in support of the  $10^0$  angle the influence of the facet angle on coupling efficiency and gain ripple is analysed both theoretically and experimentally.

The devices fabricated were based upon the  $1.5\ \mu\text{m}$  wavelength ridge waveguide laser [3] as illustrated in Fig. 1. Ridges were formed  $3.3\ \mu\text{m}$  wide, at angles of  $10^\circ$  to the facet normal by a  $\text{CH}_4/\text{H}_2$  RIE process. A larger angling of the facets results in a smaller fraction of the power reflected from the facet being coupled back into the waveguide, yielding a lower modal reflectivity. The use of the dry etching technique avoids the problems of mask undercut for off axis ridges. Wafers grown by LPE were used, with  $0.15\ \mu\text{m}$  thick active layers, and  $0.3\ \mu\text{m}$  thick anti-meltback layers. To reduce the facet reflectivity further a single layer quarter wavelength anti-reflection coating is applied. This is formed by electron beam evaporation of a commercially available compound (substance 1) manufactured by Merck. Figure 2 shows a measured spectral gain-ripple of 0.025 dB at a single-pass gain of 21 dB. This corresponds to a modal reflectivity of  $1 \cdot 10^{-5}$ , which is comparable to the best reflectivity reported while the employed AR-coating technique is relatively simple.

The coupling efficiency between fiber and amplifier is as important as the modal reflectivity. For the  $10^0$  devices, we have obtained coupling efficiencies to tapered lens-ended fibers of -3.3 dB. This is close to the coupling efficiencies for normal-facet devices as seen from Fig. 3, which gives the theoretically and experimentally determined excess coupling losses as a function of the facet angle. Results for three different lens radii of the tapered lens-ended fiber are given. A lens radius of  $11\ \mu\text{m}$  provides the best results for the waveguide structure employed. The excess coupling losses of 0.2-0.5 dB for  $10^0$  angled devices are acceptable in view of the low modal reflectivities obtained.

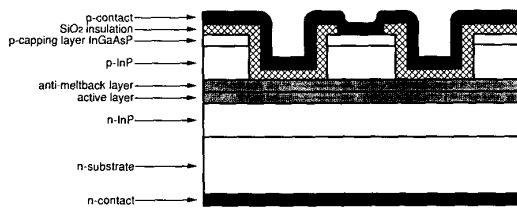
Higher-order transverse modes can cause a higher modal reflectivity because of coupling between the modes at the facets. The gain-ripple vs. facet angle with and without the presence of the first-order mode is derived from a three-dimensional model [4] as shown in Fig. 4. The single-pass gains for the fundamental and the first-order modes are 25 dB and 15 dB, respectively. As seen, the excess gain-ripple due to the first-order mode is nearly eliminated by angling the facet at  $10^\circ$ , implying that the  $10^0$  devices are more immune to higher-order modes, should they be present.

In conclusion,  $10^0$  angle-facet SLA's are reported. The larger angling ensures a lower gain ripple, while maintaining a coupling efficiency as high as -3.3 dB.

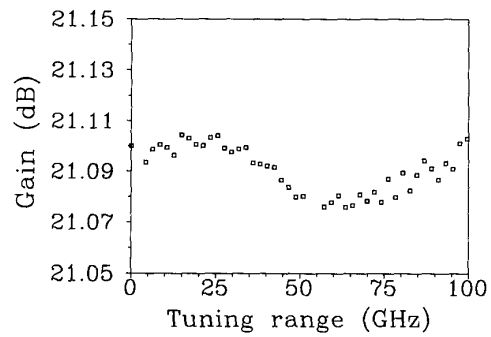
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**References:**

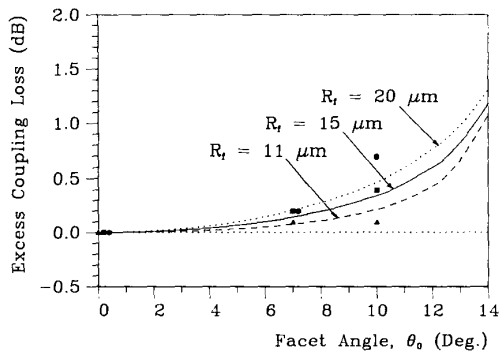
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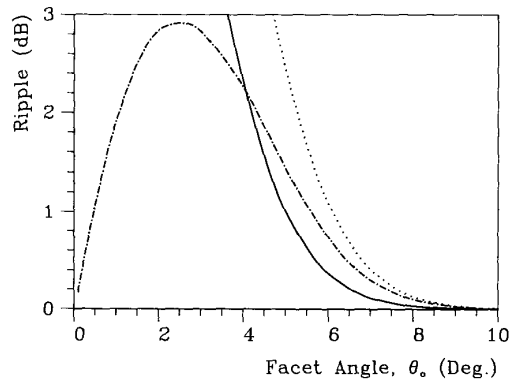
**Figure 1:** Schematic cross-section of the ridge waveguide structure.



**Figure 2:** Gain vs. input frequency for a 10° angle-facet SLA.



**Figure 3:** Theoretical and experimental excess coupling loss vs. facet angle. The lens radii,  $R_f$ , for the tapered lens-ended fibers are: 11  $\mu\text{m}$  (---,  $\blacktriangle$ ), 15  $\mu\text{m}$  (—,  $\blacksquare$ ) and 20  $\mu\text{m}$  (····,  $\bullet$ ).



**Figure 4:** Gain ripple vs. facet angle for 25 dB single-pass gain. Fundamental mode (—), fundamental and first-order mode (····), excess ripple due to first-order mode (-·-·-·).